SPATIAL AND SITING ANALYSIS OF SUSTAINABLE BIOMASS BASELOAD POWER GENERATION FOR NIGERIA

by

Adedolapo Oluyomi Akinde

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Approved by:

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Dr. Jy S. Wu

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Dr. Peter Schwarz

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Dr. John Diemer

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Dr. Hilary Inyang

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Dr. Ahmed El-Ghannam

ABSTRACT

ADEDOLAPO OLUYOMI AKINDE. Spatial and siting analysis of biomass baseload power generation for Nigeria. (Under the direction of DR. JY S. WU)

A new dawn in Nigeria's power generation landscape requires renewable energy development. Episodic power supply, and too frequent outages characterizes the centralized power grid in Nigeria, thus frustrating efforts towards economic development. The current situation of electricity generation calls for a diversified energy mix with an increasing share of renewable based electricity generation for sustainable development. Biomass is promising as flexible, able to ramp, cost efficient, and reliable for baseload renewable electricity generation without intermittency, and possibility for integration without any additional backup. The study focus is on maize crop residue-based biomass-fired power plants for energy development using data from the wet season agricultural performance survey. Land use productivity in the cultivation of crops providing biomass residue feedstock is key to growth and has a priority spot in the policy discourse among stakeholders in Nigeria. Moreover, facility siting as in the case with power plant is a vital part of planning, impacting on profitability and viability of ventures. We employ a policy-driven, multi sectoral-focused approach in solving spatial multi state power generation planning problem. The study conducts suitability analysis and solves location-allocation optimization for siting decision. Results reveal suitable states for biomass-fired baseload generation using maize residue as feedstock. Findings suggest an actionable pathway to chart biomass-fired baseload power generation siting plans in Nigeria. Harnessing crop residue as feedstock in biomass-fired electricity generation subscribes to the concept of circular economy as an alternative to traditional linear economy. Circular economy pushes for a shift to renewable energy and materials, seeks to extract the maximum value from crop output, and deploys biomass power generation technology. Such electricity generation improvements will enhance competitiveness of the entire commercial and industrial sectors in Nigeria thereby enabling the unleashing of productivity across the board through a reduction in structural impediments to Nigeria's industrialization. Core implication of the research approach through productivity index is the opportunity for government regulatory operations through productivity improvements in enhancing energy infrastructure permitting.

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DEDICATION

This dissertation is dedicated to my biological parents, Venerable and Mrs. Akinde for their manifold parental roles and sacrificial investments through the many years of my academic training. And to my siblings for their multi-dimensional contributions towards completion of the degree program.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ADP	Agricultural Development Programs
APA	Agricultural Promotion Policy
CAES	Compressed Air Energy Storage
DFISS	Department of Farm Inputs and Support Services
ECN	Energy Commission of Nigeria
FCS	Federal Constituency Seats
FCT	Federal Capital Territory
FDA	Federal Department of Agriculture
FDAE	Federal Department of Agricultural Extension
FDAPHS	Federal Department of Animal Production and Husbandry Services
FDFA	Federal Department of Fisheries and Aquaculture
FEWSNET	Farming Early System Warning Network
GHG	Greenhouse Gases

GIS	Geographic Information System
IAR	Institute for Agricultural Research
IRENA	International Renewable Energy Agency
IRP	Integrated Resource Plan
LGA	Local Government Area
MITI	Federal Ministry of Industry, Trade, and Investment
MDGs	Millennium Development Goals
MW	Megawatt
NAERLS	National Agricultural Extension and Research Liaison Services
NAPRI	National Animal Production Research Institute
NBS	National Bureau of Statistics
NDP	National Development Plan
NECAL	Nigeria Energy Calculator
NEP	National Energy Policy
NERC	Nigerian Electricity Regulatory Commission
NESO	Nigeria Electricity Supply Operator

NGCC	Natural Gas Combined Cycle
NIIMP	National Integrated Infrastructure Master Plan
NIMET	Nigerian Meteorological Agency
NIRP	Nigeria Industrial Revolution Plan
NNPC	Nigerian National Petroleum Corporation
NPC	National Productivity Center
PHCN	Power Holding Company of Nigeria
P&PCD	Planning and Policy Coordination Department
PPP	Public Private Partnerships
PV	Photovoltaic
REIPPPP	Renewable Energy Independent Power Project Procurement Program
REMP	Renewable Energy Master Plan
RPR	Residue Product Ratio
SMEs	Small and Medium Enterprises
WSAPS	Wet Season Agricultural Performance Survey

CHAPTER 1: INTRODUCTION

1.1 Background

Power outages are a fundamental infrastructural issue hindering productive activities in Nigeria (Federal Ministry of Industry, 2014). Nigeria currently generates less than 5,000MW from installed capacity, a far cry from the stakeholders' estimate of 140,000 - 160,000MW (see Appendix 1). Meanwhile, electricity from self-generation through petrol and diesel generators is nearly over 6,000 MW (The World Bank, 2018c). Nigerian small and medium enterprises (SMEs) lose about 15.6% of sales value to power outages (The World Bank, 2014) translating to about $12.6 billion dollars based on 2013 retail sales value (National Bureau of Statistics, 2013).

Studies links the challenging electricity situation in Nigeria to relocation of about one-third of Nigerian manufacturing companies out of Nigeria to Ghana and Republic of Benin, neighboring countries with stable and uninterrupted electricity supply (Mbisiogu, 2013). Nigeria is mainly agrarian with agriculture contributing about 25% to the national gross domestic product (GDP) and providing employment for about 70% of the populace. Woody biomass fuels (such as sawdust, industrial wood chips, bark, and forest wood chips), herbaceous biomass residues (such as grasses, straw, cereals residues), alternative biomass fuels (such as rice husks, kernels, and shells), and animal waste are available for biomass power generation.

This research focuses on residues from crop production. Agricultural crop residues are often associated with zero value at disposal. Therefore, biomass power generation comprising “waste-to-energy” conversion constitute a value addition process with economic and market potential (Wu et al., 2017). Reliable information on crop and livestock production in Nigeria is available through the wet season agricultural performance survey in published reports by the National Agricultural Extension and Research Liaison Services (NAERLS). For this research, data from 13years of the survey (2005 – 2017) are used.

This study focuses on maize stalks as the feedstock for biomass power generation. Maize is the most cultivated and abundant arable legume crop in Nigeria. Maize also is a major energy crop for biomass electric power generation across Europe (Schievano et al., 2015). In contrast to maize, the data for waste from livestock such as cattle, sheep, goats, and pigs are difficult to obtain since they are mainly free ranging across local government area (LGA) borders. Likewise, data on poultry wastes are also inconsistent in time and space. World development indicators of the World Bank show electricity generation infrastructure in Nigeria is mainly gas-fired (about 82.4%) and hydropower (about 17.6%), which suffer from security of gas supply and seasonality of water levels respectively (The World Bank, 2018b).

However, rich biomass resources in the form of crop residues, animal wastes, forage grasses, municipal, and industrial activities including aquatic biomass such as water hyacinth, are available all over Nigeria for power generation. Electric security concerns pave the way for diversification of energy supply mix from fossil fuel to renewables generation (Saifuddin et al., 2016; Ahmed, 2018). Environmental impacts of greenhouse gases (GHG) and harmful emissions from burning fossils fuels provide impetus for integration of renewable energy towards reduction in carbon emission, and a cleaner environment and simultaneous increase in power generation.

The severity of electricity supply shortages and power outages calls for reliable baseload generation. This study focuses on utilization of crop residue biomass resources to enrich the energy mix up to 4,557.2 Gigajoules renewable energy (equivalent to 1,265.9 MWh electricity consumption), turn an environmental liability into an asset, ensure a clean environment, and generate baseload renewables electricity as a cost efficient and reliable power supply in Nigeria (Bilal et al., 2016; Energy Commission of Nigeria, 2013; Matek and Gawell, 2015; Shafiullah, 2016). Biomass is a commercially viable renewable energy source (Schwarz, 2017).

Biomass can serve as a renewable baseload power source having generation profiles that can economically substitute for other retiring electricity sources megawatt for megawatt, thus avoiding incurring additional costs associated with purchasing and then balancing renewable intermittent power sources through storage or new transmission (Matek and Gawell, 2015). Deployment of baseload renewable energy like biomass is key in meeting electricity demand effectively and in avoiding higher ratepayer costs associated with additional ancillary services required to curb over generation by intermittent renewable energy sources especially solar energy.

By enhancing energy mix, biomass power helps to maintain a sustainable supply of feedstock and fuels for electricity generation that shields consumers from potential shortages or price spikes. Renewable baseload sources like biomass are generally cheaper or equivalent in price to intermittent power sources like wind and photovoltaic (PV). But wind and photovoltaic cannot provide baseload generation. Biomass resource assessment and baseload generation at varying scales abound in many parts of the world. Groundnut oil industry in the Gambia generates all 4.5 MW electricity by groundnut shells (Energy Commission of Nigeria, 2012). Analysis of oil palm biomass potential show electricity generation from biomass plants reaches 35 MW in Indonesia (Nasution et al., 2014).

In the U.S, Piedmont Green Power LLC runs a 55 MW biomass-fired generating facility using woody biomass from urban wood waste, mill and logging residues. Also, the Gainesville Regional Utilities operates a 102.5 MW woody biomass-fired plant (U.S DOE, 2016a). Sugarcane industry in Mauritius generates surplus electricity in almost all the sugar mills with total installed capacity at 243 MW (Zafar, 2018). In Malaysia, study shows biomass potential can supply up to 20 suitable locations with total capacity of 4,996 MW using oil palm biomass residues from oil palm plantations (Yun Seng et al., 2014).

Their study considers the capital and operation costs of the power plants as well as the connection of the power plants to the national grid. In Nigeria, there are currently no such data on costs as there are no operational biomass power plants. Nigerian National Petroleum Corporation (NNPC) and Kogi state government have recently signed a memorandum of understanding (MoU) to construct the first commercial biomass power plant in Nigeria using sugarcane bagasse from within Kogi state. The biomass project in Kogi state includes a bagasse-fired power generation facility that can generate up to 64MW electricity, which is behind schedule of the renewable energy master plan (REMP) 2015 target of 50 MW biomass (Ughamadu, 2018; Olaoye et al., 2016).

Residue feedstock for this project will come from a 20,000 hectares sugarcane plantation and or 15,000 hectares cassava plantation with potentials for further expansion. Prioritizing national development over a single state interest and considering efficiency and productivity of the agricultural sector supplying biomass feedstock for biomass plant operations, pertinent questions arises. On a national scale in realizing Nigeria's overall growth and development objectives, which state serves as best optimal location in a multi-state analysis? What states will be optimal site in a multi-state siting plan?

1.2 Overview of Nigeria Energy Resources and Development

Despite the geo-economic peculiarities of Nigeria with its unreliable electric power supply, the topics of energy security and environmental pollution due to dependence on fossil fuel, are as popular as in any other part of the world. Crude oil and natural gas have been main-stays of Nigeria's energy economy in recent decades, especially for foreign exchange. Yet, the nation is caught in the web of a full-blown energy crisis with near zero electricity supply in many places, including major commercial hubs and industrial areas despite abundant gas resources. The reason is not a lack of energy resources, rather, the energy supply system in Nigeria is characterized by an aging, obsolete infrastructure with incessant breakdowns and suboptimal outcomes in generation due to widespread redundancy of power infrastructure (Office of the Vice President, 2015; Makwe et al., 2012). Records show that between 2009 and 2012, there were about 124 cases of system collapse along the electricity supply infrastructure in Nigeria (Simon, 2014).

In Nigeria, crude oil, tar sands, and natural gas are available in huge deposits (see Appendix 6). While there are no proven deposits of radioactive ores, coal deposits comprise more than 2 billion tons. Solar radiation ranges from 4 kWh/m^2 in the south to nearly 7 kWh/m^2 in the north. Wind speeds also are greater in northern Nigeria than in the southern regions, with values ranging from 1m/s in the south to 7.96m/s in northern regions. Under-utilized hydropower potential stands at about 12,954 MW which exceeds the 10,000 MW baseline to stir socio-economic growth and poverty alleviation. Annual estimate of dry biomass from shrubs and forage grasses sum to about 200 million tons with approximately 2.28×10^6 MJ of energy out of which over a million ton of that biomass can be harnessed for electricity generation (equivalent to 4,720 GWh) but is not currently being utilized (Oyedepo, 2014; Energy Commission of Nigeria, 2012; Mohammed et al., 2013).

1.3 Problem Statement

This research seeks optimal utilization of the massive untapped biomass potential for baseload electric power generation in the Nigeria electricity supply industry. Less than 55% of Nigeria's population has access to the centralized national grid electricity supply (Nebo, 2014; The World Bank, 2017). Provision of energy infrastructure facilitates the basic workings of a society through provisioning of essential services that drive socio-economic growth and development (Bazilian, 2015). Reform programs in the Nigerian Electricity Supply Industry (NESI) is supposedly one of the most ambitious privatization exercises globally with a transaction cost of over three billion U.S dollars ($3.0bn).

Privatization of the generation and distribution segments of the unbundled power sector intends to ride on the heels of a thriving telecommunications industry privatization. However, there has been no notable improvement in the delivery of electricity. While solar and wind cannot provide baseload electricity, hydro suffers setbacks from ecological issues such as flooding, and seasonality issues associated with water levels. Hydro and gas power infrastructure facilities are old and beset by water flow problems and gas disruption and supply problems. Recent developments in the Nigeria power sector indicate the possibility of re-evaluation of the privatization scheme and likely reassignment of operating licenses.

New entrant utilities must necessarily be on the analytic edge of efficient use and optimal deployment of units of production. Wind and solar are intermittent sources that can neither cost-effectively generate electricity for a balanced grid nor supply baseload power. Baseload power sources consist those plants that operate continuously to meet the minimum level of power demand. A baseload threshold exists below which every electrical grid suffers outages or system failures (Emodi and Boo, 2015a; Energy Commission of Nigeria, 2013; Geothermal Energy Association, 2016). Biomass is an appropriate firming resource for a renewable future.[1] Firming generation is constant power generation which is guaranteed. By application of facility site location-allocation, the research question is as follows:

Is it possible to simultaneously locate a set of biomass-fired baseload electricity generating facilities to minimize weighted transport distance of available energy potential site to target population, where weighted distance is a proxy for accessibility as an efficiency measure**?**

Solving this optimization problem involves closest facility assignment.

1.4 Technical, Economics, and Market Issues

For various capacities of renewable energy projects Nigerian Electricity Regulatory Commission (NERC) approves a renewables' feed-in tariff (FIT) for grid-connected renewable energy projects, thereby allowing for a diverse and resilient energy mix. Categorized benchmark capacity for biomass is 1 – 10 MW (Brand and Missaoui, 2014;

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[1] Firm power refers to "power-producing capacity, intended to be available always during the period covered by a guaranteed commitment to deliver, even under adverse conditions" (U.S DOE, 2018).

Huenteler, 2014). The FIT for biomass capital cost, and operation and maintenance costs is US $112/MWh, and $42.71/MWh respectively in the base year 2016 (Akinsoji, 2016). FIT boosts implementation of renewable energy projects and attracts fresh investments. Fresh investments enable greater uptake of renewables integration on the grid leading to an increasing trend in the energy mix over time.

Learning from Japan, generous returns for renewable energy investments in the Japan FIT scheme has a tremendous positive impact in stimulating investments towards renewable power generation (Hughes, 2013). Siting of a renewable power facility is a major determinant of economic profitability. Spatial analysis, therefore, is key to sustainable energy planning and development as feedstock and fuel materials that serve as resource inputs are usually spatially distributed. Marlan and Rosemary Bourns College of Engineering Associate Professor, Hamed Mohsenian-Rad, who leads a team recently awarded $3.2 million by the U.S. Department of Energy to develop an energy management system for renewable integration stated "when the power grid was set up, it was designed to handle power from conventional sources, but now we must consider capacity and location of these units, and the penetration of renewable energy technologies"[2] (Nightingale, 2017).

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[2] Biomass energy technologies for power generation encompasses, biogas, bio-fuels, and biomass briquetting. Biogas is a combination of 60 - 70% methane (CH_4), 23 - 38% carbon dioxide (CO_2), 2% hydrogen (H_2) and traces of hydrogen sulfide (H_2S). Biogas is produced by anaerobic digestion (that is, fermentation) of organic materials and its lower heating value is approximately 6 kWh/m^3 (Energy Commission of Nigeria, 2012).

For a power-only (that is, not combined power and heat) biomass steam system in the range of 5 - 25 MW, costs generally range from US $3,000 to $5,000 per kilowatt of electricity (kWh) in the U.S (U.S DOE, 2016b). System cost intensity tend to decline as the size of the system increases. In the U.S, levelized cost of energy (LCOE) ranges from US $0.08 to $0.15 per kWh for power-only systems, with the potential to increase with fuel costs. In Nigeria, back-up diesel generators cost of energy (COE) is about US $1.075/kWh, while the national grid charges a maximum of about N48.35kobo/kWh which is an equivalent of US $0.13 per kWh (Energy Commission of Nigeria, 2012; Olatomiwa et al., 2015; Narnaware et al., 2017). By comparison, biomass power in Malaysia utilizes rice husks from rice mills in generating electricity at a unit cost of approximately US $0.03 per kWh.

Factors driving biogas and biomass technology market cost-effectiveness in Nigeria include: technology transfer and technology management; security of supply through initiatives that increase energy choices and promote adaptability to change; improved safety of energy transport facilities; and environmental considerations towards sustainable energy use. Technological advances, transfer, and management have the potential to serve as an enabler for the acceptance, implementation, and improvements of options that would otherwise have gained minute segments of the energy mix (Inyang, 2006). Biomass power augments the diverse mix of electricity sources thus ensuring grid stability and security, and reducing the overall risks of volatility (HIS, 2014).

However, there are barriers to market development of biogas and biomass energy resources. While both biogas and biomass are biofuels, there is a distinction in the energy production process. Basically, biomass involves burning of organic feedstock while biogas involves use of microorganisms in anaerobic digestion to produce biogas. Such barriers include: technical challenges due to inability to utilize necessary technology; lack of transparent sharing of data and information; time requirement to effect change; informal waste collection systems; environmental degradation from biomass use, uneven distribution of biomass resources for utilization in electric power generation and supply; and financial limitations due to competing investments for funds by other sectors (Energy Commission of Nigeria, 2012).

1.5 Research Objectives and Contribution to Knowledge

Nigeria's economic recovery and growth plan (ERGP) known as vision 20:2020 identifies electric power supply as a major constraint to economic growth. Major shifts in preferences, cost efficiency, service quality improvement, and mitigation of adverse environmental impacts are core to sustainability. This study employs GIS for site suitability analysis in determining potential sites for biomass power plant in Nigeria. Finally, the study investigates a feasible solution for optimally siting biomass-fired baseload power plants across multiple states.

Overall, the objective of the study is to achieve cost efficiency in providing reliable baseload electricity supply through minimization of a weighted cost objective for optimal utilization of biomass feedstock in the energy mix in Nigeria.

Specific objectives of the study include:

i. Determining suitable site(s) of single and multiple facilities for baseload biomass power plant(s) in Nigeria, thereby improving clean energy development.

ii. Optimizing multi-state location-allocation siting decisions for biomass baseload electricity generation, thereby shaping energy infrastructure planning and permitting.

iii. Policy and Economic Assessment of Biomass utilization for Nigeria, thereby contributing to the execution of the National Biomass Energy Program.

Location-allocation modelling for power plant siting based on productivity index has never been done in the energy and power sector of Nigeria. This study makes contribution as part of waste-to-energy development is on harnessing productivity in the agro-ecological economy of maize cultivation in Nigeria for baseload electricity development. Baseload electricity supply alongside improvements in the quantity and quality of energy services is strongly linked to the realization of Millennium Development Goals (United Nations, 2015). Millennium Development Goals (MDGs) include: achieving universal primary education, ensuring environmental stability, halving extreme poverty rates, and improving agricultural productivity.

Thus, beyond mere consideration for abundance of crop residue, this research identifies locations of high agricultural productivity. By implication, we identify areas of best production technology as suitable locations and sources of crop residues that could serve as feedstock for biomass baseload electricity generation.

1.6 Synopsis of Wet Season Agricultural Performance Survey

The wet season agricultural performance survey (WSAPS) is a key annual activity of the National Agricultural Extension and Research Liaison Services (NAERLS). The 2017 WSAPS was carried out by NAERLS in collaboration with the Federal Department of Agricultural Extension (FDAE), Planning and Policy Coordination Department (P&PCD), Federal Department of Agriculture (FDA), National Bureau of Statistics (NBS), Federal Department of Fisheries and Aquaculture (FDFA), Federal Department of Animal Production and Husbandry Services (FDAPHS), and the Institute for Agricultural Research (IAR).

Other agencies involved include the Department of Farm Inputs and Support Services (DFISS), National Animal Production Research Institute (NAPRI), Nigerian Meteorological Agency (NIMET), National Productivity Center (NPC), Farming Early System Warning Network (FEWSNET) and 37 state Agricultural Development Programs (ADPs). The 2017 WSAPS took place between 20th and 27th August 2017. Data capturing from the farmers was done using electronic devices like Android tablets as part of efforts to add value to the survey in terms of quality, utility and depth of data generated. Questionnaires for ADPs, ministries and other agencies were carried out using written records.

The annual survey comprises:

i. An evaluation of the performance of crops and livestock during the season and estimation of outputs;

ii. Identification of constraints to increased agricultural productivity;

iii. Identification of conditions affecting effective technology transfer and advisory services within the season; and

iv. Providing feedback on field conditions and farmers' problems for enhanced research and policy performance.

The methodology for data collection in WSAPD consists of the following steps: First a questionnaire survey, and then a Participatory Rural Appraisal (PRA) was performed across 36 states and the Federal Capital Territory (FCT) by nineteen multidisciplinary teams of three scientists each, making a total of 57 scientists. In every state, the teams visited two ADP zones. In each zone, two Local Government Areas (LGAs) were selected and one community was selected per LGA. In each community, interviews were done with five farmers and focus group discussions were held. Meetings and extensive discussions were held with ministry officials, ADP staff, and staff of other relevant agencies. Validation of data and findings with officials of the state ADP and Ministry of Agriculture concluded the wrap-up sessions at the end of each state visit.

Subsequent chapters describe progress towards achieving the research objectives; Chapters 2, 3, and 4 focus on the first, second, and third specific objectives respectively. Chapter 2 presents site location analytics using GIS, a visualization tool. Chapter 3 deals with location-allocation modelling for multi-state siting decisions using LINGO software. Chapter 4 presents policy and economic assessment of biomass utilization for Nigeria. Chapter 5 comprises economic and policy implications of biomass utilization for Nigeria. Chapter 6 comprises conclusions and recommendations based on research findings.

CHAPTER 2: POWER PLANT SITE SUITABILITY LOCATION ANALYTICS

2.1 Global Energy Development and Nigerian Industrial Revolution Plan

Energy development across the globe over the last decade has included both fossil fuel and renewable energy resources. State-of-the-art technological advances and cutting-edge improvements in extraction methods to harness energy resources through processes like hydraulic fracking, and clean coal are indicative of many aspects of this transformation to meet the increasing demand for energy. Conventional energy production releases greenhouse gases (GHG) from fossil fuels, thus posing adverse environmental and health impacts (Zahran and Beshr, 2013; International Energy Agency, 2016).

Concerns about carbon dioxide (CO_2) emissions are widespread, as are concerns about other air pollutants which are linked with premature death. Furthermore, pollution from fossil fuels triggers community disenchantment with exploration and extraction of energy resources thereby raising questions about the role of fossil fuels as the dominant energy source for modern industrialization (Oates and Jaramillo, 2013; Farquharson et al., 2016). The Nigerian Industrial Revolution Plan (NIRP) is the nationwide roadmap for industrialization (Federal Ministry of Industry, 2014). NIRP identifies electric power outages as a major systemic issue responsible for the failure of previous industrialization plans in Nigeria (Bazilian, 2013).

NIRP was developed in 2015 by the Federal Ministry of Industry, Trade, and Investment (MITI) as Nigeria’s first strategic, all-inclusive, and integrated road map to industrialization. The plan targets efforts in developing sectors, where the nation has a natural relative advantage, thereby guaranteeing that industry in general turns out to be competitive by turning quantity advantage into productive advantage. Studies show that the manufacturing industry is a determinant for both long-run and short-run electricity consumption in Nigeria (Ubani, 2013; Ngutsav, 2014). Sectors like agriculture and mining where the nation has a natural advantage will play the role of “anchor sectors” in driving Nigeria’s industrialization.

Disruption-free production of goods and services require ample generation capacity and robust transmission and distribution networks (National Planning Commission, 2015). The NIRP places the services sector, which includes electricity supply, and agribusiness or agro-allied sectors in the category of anchor sectors. Therefore, the spatial distribution of productive of agribusinesses that supply crop residues which serve as feedstock for biomass electric power generation is critical (Federal Ministry of Industry, 2014). Site location and suitability analysis are key to developing a sustainable energy system (Wu et al., 2017; Höhn, 2014; Church and Murray, 2009; Inyang, 2006).

There has been no study in Nigeria on biomass electric power generation based on land use productivity and production cost efficiency. The sustainable supply of feedstock is vital to the efficient operation of biomass electric power plants for baseload generation. As expected, areas of high biomass productivity are promising locations for biomass power plants. An empirical procedure in site location analysis is Suitability Analysis (Church and Murray, 2009). So, which states in Nigeria are suitable sites for biomass power plants based on agricultural productivity per unit land area?

2.2 Resource Assessment, Suitability Analysis and Agriculture Promotion Policy

Baltazar et al., (2016) performed biomass resource assessment with mathematical models and LANDSAT-based land cover map in the Philippines. Maps of theoretical biomass potential and available biomass potential were derived. Their study used LiDAR data for suitability analysis but omitted transport cost of rice hulls. Höhn et al., (2014) analyzed the spatial distribution of potential biomass feedstock and the amount of feedstock for bio-methane production in southern Finland. Their study found that accurate estimates of transportation distances serve as valuable information during the planning stage and are useful in calculating CO_2 emissions and associated investment and transportation costs accurately.

An important component of suitability analysis is the sustainability concerns of state and federal natural resource departments having interest in areas where flora and fauna habitat is threatened by facility siting. In facility siting, a process of defining potential locations is often required. The reason is that some critical infrastructures, such as power generation facilities, simply cannot be located haphazardly (Church and Murray, 2009). In 2012, Nigeria's core infrastructure stock stood at about 20-25 per cent of GDP which is equivalent to less than USD 100 billion (National Planning Commission, 2015). In contrast, international benchmarks for core infrastructure stock was set at about 70 per cent.

Suitability analysis is essential, as some locations are better than others depending on the purpose of the facility being sited (Church and Murray, 2009; Inyang, 2006). The first law of location science states that: "some locations are better than others for a given purpose". In other words, efficient system locations tend to beat inefficient ones. Consequently, an efficient location pattern persists longer than inefficient ones for a specific use, holding all other factors constant. No doubt, what is finally considered suitable is a function of the type of facility to be sited. With a set of known feasible sites, it is possible to explore issues of performance and service provision (Church and Murray, 2009).

Least cost per unit land and high productivity can be related to efficient farm performance and service provision respectively. If some locations are better than others for a specific purpose, which in this case is productivity in the maize feedstock supply chain, what then are the superior locations at which to site multi-state biomass power generation facilities? In the year 2010, in a bid to refocus the agricultural sector, the

Nigerian government implemented a new strategy known as the Agricultural Transformation Agenda (ATA) (Federal Ministry of Agriculture and Rural Development, 2016).

Nigeria currently faces two key gaps in agriculture which include: failure to meet domestic food requirements, and failure to export at levels required for market success. The former problem exemplifies a productivity challenge due to an input system and an inefficient farming model. The latter challenge is influenced by an equally inefficient system for setting and enforcing food quality standards, which is not unconnected to inadequate power supply necessary for preservation of farm produce quality and reduction in post-harvest losses. In fact, the Agriculture Promotion Policy identifies the power sector as vital to achieving these goals and objectives.

The National Economic Management Team unveiled an Agricultural Transformation Agenda (ATA) to rejuvenate the agricultural sector. Objectives of ATA include: increasing food and nutritional security; providing correct policy, regulation and administrative framework; enhancing income of the rural populace; creating employment and jobs (with a goal of adding about 3.5 million jobs by 2015); increasing export earnings; and reducing import dependency. That strategy was in effect from 2011 to 2015. In 2015, the Federal Government rolled out broad-based programs with the intention to trigger investment-driven strategic partnerships.

Such partnerships targeted the private sector and delivered a range of incentives to unlock the potentials of agriculture to upturn the sector contribution to economic growth. Under ATA, Nigeria took giant strides to advance market connections and boost commodity value chain performance by promoting innovative incentive schemes (Federal Ministry of Agriculture and Rural Development, 2016). Thus, ATA's focus was on making Nigeria's agriculture more effective, efficient and productive. The purpose of the ATA policy document was to deliver a disciplined approach in building an agribusiness ecosystem poised to solve these two gaps.

Thus, it became paramount to "refresh the ATA strategy" to tackle these two issues. The Agricultural Promotion Policy (APP) is the new refreshed strategy and refreshed policy regime. One of the APP's objectives for the 2016 – 2020 period is the integration of agricultural commodity value chains into the broader supply chains of Nigerian and global industry, increasing the contribution of agriculture to wealth creation, and driving job growth. Nigeria's APP centers around three organizing themes which include: productivity enhancements, crowding in private sector investment, and Federal Ministry of Agriculture and Rural Development (FMARD) institutional alignment.

Access to land is the first performance metric under productivity enhancements in the APP. The bottom line is that location matters due to productivity concerns. Land for large scale crop production may not be available in one state (such as Lagos state) of the country. In other cases, available land may be unsuitable due to low productivity.

Consequently, opportunity costs might warrant putting such land to an alternative crop-based use. Land use productivity in agriculture is a central theme in Nigeria's Agriculture Promotion Policy (APP) (Federal Ministry of Agriculture and Rural Development, 2016). Thus, this research encompasses a productivity index as part of encouraging efficient agricultural production (See Appendix 3 for normalized productivity per unit land for maize cultivation across Nigerian states in the six agro-ecological zones).

Best practice requires normalization of data when the origin does not converge in graphing. Plots show irregularity of pattern in productivity thereby suggesting some noise which data fails to capture. Crop residues that serve as feed stock are non-major commodities, yet they are an integral aspect of the value chain with diverse uses in the economy ranging from rural household uses to industrial applications as biomass feedstock in electric power generation. Biomass power development is promising as an end-to-end value chain solution for enterprise development across successive stages of the commodity value chains.

In alignment with APP's drive for productivity, there is interest in siting a biomass fired power plant with corn stalks as feedstock only in states with least cost per unit land and high productivity per unit land. Maize is one of the priority crops that the Federal ministry of agriculture and rural development (FMARD) identifies for productivity improvements. In each of the states in north east, north central, and north west Nigeria, the staple cereal cultivated by most farmers is maize (National Agricultural Extension and Research Liaison Services, 2017). The maize crop is an important food crop in all the ecological zones of Nigeria (National Agricultural Extension and Research Liaison Services, 2017).

In 2017, there was an increase in the land area used to produce maize in almost all the states in Nigeria. Among three major food crops (maize, rice, and wheat) that are in line for productivity improvements, maize has the least supply deficit. A demand estimate done in 2016 for rice, wheat, and maize stands at 6.3million, 4.7million, and 7.5million tons, respectively, while supply estimates stand at 2.3million, 0.06million, and 7.0million tons, respectively, in the same year. Thus, the supply deficit in 2016 stood at about 4.0 million, 4.64 million, and 0.5 million tons for rice, wheat and maize, respectively. These figures give an indication that of the three major cereals, maize requires least improvement in productivity for matching local supply capacity to meet total demand thereby closing the demand supply gap; a major food security goal of APP. Use of crop residues implies that this study creates no competition for food production.

2.3 Methodology

Electricity generation planning is vital to economic, environmental, and social performances of a power generating system. In this research, Suitability Analysis as described in Chapter 5 of *Business Site Location Analysis* (Church and Murray, 2009) is used as a model. Suitability Analysis is a process of analytically identifying, or ranking, potential locations with respect to specific uses. The terms identifying, and ranking suggest that suitability could be either absolute or relative. Relative suitability indicates that possible locations vary with some sites being more desirable for a specific use than others.

Relative suitability analysis using GIS constitutes empirical analysis for energy facility location analysis (Höhn, 2014), and so presents a platform for policy learning that could lead towards improvement in Nigeria's power sector (Cerna, 2013). Distinct from relative suitability, absolute suitability categorizes a location as either suitable or not suitable. Thus, suitability analysis is a relevant process for power generation facility siting in line with APP. The commercial viability of power plants is linked to site suitability (Nightingale, 2017). Suitability analysis identifies feasible, or superior, locations for some designated activity as in the case of biomass power generation.

This analysis measure crop productivity per unit land as a ratio of harvest (measured in thousand tons) to estimates of land area (measured in thousand hectares) under cultivation each year (see Appendix 5 showing annual productivity index mapping of states in wet season maize cultivation for each year from 2005 to 2017). We measure cost per unit output as the amount of money spent (measured in Naira – the local currency) per unit land area (measured in hectare) for maize production each year. WSAPS reports cost values and variation across states is essentially a function in cost of production inputs such as land, tractor services, labor, etc.

Table 2.1 presents summary statistics of key variables of maize production in Nigeria across the 36 states and Federal Capital Territory (FCT). While high productivity per unit land area is desirable, the least-cost per unit land area is desirable for facility location. We employ this “shopping list” of attributes/variables to construct a composite index.

Table 2.1: Summary Statistics of Maize Crop Production in Nigeria

Statistic	*Mland*	*Mharvest*	*MCostProd*
Mean	154.922	3102.772	184.097
Standard Error	14.659	364.351	19.139
Median	150.8	2457.828	166
Mode	N/A	N/A	165
Standard Deviation	89.165	2216.259	116.420
Sample Variance	7950.323	4911802.741	13553.67
Kurtosis	3.724	3.575	7.056
Skewness	1.563	1.617	2.300
Range	430.8	10578.499	607.5
Minimum	43.35	555.811	45
Maximum	474.15	11134.31	652.5
Sum	5732.1	114802.549	6811.6
Count	37	37	37

Terms	Variable Description	Measurement Unit
Mland	Mean Estimate of Land Area for Cultivation	Thousand Hectares
Mharvest	Mean Harvest	Thousand Tons
MCostProd	Mean Production Cost Per Unit Land Area	Thousand Naira per hectare

Source: National Agricultural Extension and Research Liaison Services (2017)

The composite index is derived by dividing the mean cost per unit land by the mean productivity per unit land. This composite index is termed "mean combined cost productivity ratio index", denoted as "**MCCPRI**". The first step is resource assessment. WSAPS provides information on total annual production of crop harvest. Availability is a key indicator of energy sustainability (Inyang, 2006). From published papers we estimate the quantity of crop residues in each study area to calculate the residue theoretical potential (T_n) (Koopmans and Koppejan, 1997). The formula for T_n is as follows:

$$CR_n = \sum_n H_n Y_n \tag{2.1}$$

where:

CR_n = biomass theoretical potential for crop n (measured in residue ton per year, residue/year)

H_n = harvest amount for crop n (measured in tons per year, t/year)

Y_n = residue yield for crop n (measured in residue ton per harvest ton, residue/t).

This research deploys MCCPRI to screen out those states in Nigeria that do not match the desired characteristics for siting a biomass electric power facility. Consequently, we identify states that are suitable for siting maize-based biomass power plants (and those that are unsuitable). We may even further consider land cost, and then choose the least-cost feasible parcel. Absolute suitability comprises determining whether a state is suitable or not. On the other hand, relative suitability involves computing the degree of suitability of a state for the intended purpose. Thus, states are not merely binary (that is, suitable or unsuitable).

Rather, states have a classified range of suitability. In this study, attribute layers that capture land use in a comparative way are employed. Table 2.2 presents a summary of the mean (and standard deviation values in parenthesis) of land area, biomass residue potential, renewable energy potential, and baseload potential in each of the 36 states and FCT in Nigeria over the year 2005 – 2017 period.

Table 2.2: Summary Statistics of Cultivated Land for Maize, Biomass Resource Potential, and Baseload Electricity Potential in Each State

State	**Mean Land Area, ha**	**Maize Biomass Residue Potential, x10^3 tons**	**Renewable Energy Potential, GJ**	**Baseload Electricity Potential, MWh**
Borno	327.3 (126.9)	921.9 (379.9)	1844.0 (759.8)	512.2
Yobe	66.9 (56.3)	234.4 (272.2)	468.8 (544.4)	130.2
Bauchi	190.4 (78.0)	980.2 (474.7)	1960.5 (949.4)	544.6
Gombe	149.5 (27.0)	664.2 (284.0)	1328.5 (568.0)	369.0
Adamawa	150.4 (44.4)	648.3 (302.7)	1296.6 (605.3)	360.2
Taraba	289.7 (41.7)	1078.1 (83.9)	2156.1 (167.7)	598.9
Sokoto	69.6 (54.2)	139.7 (129.5)	279.3 (258.9)	77.6
Kebbi	106.1 (61.3)	361.6 (216.5)	723.2 (433)	200.9
Zamfara	95.0 (69.2)	349.3 (312.6)	698.6 (625.2)	194.1
Katsina	193.1	670.1	1340.1	372.3

	(56)	(268)	(535.1)	
Jigawa	80.7 (77.1)	318.2 (305.1)	636.3 (610.3)	176.8
Kano	175.7 (61.1)	982.1 (370.9)	1964.1 (741.9)	545.6
Kaduna	393.3 (50.7)	2141.2 (302.8)	4282.4 (605.6)	1,189.6
Plateau	212.8 (55.3)	1257.9 (309.5)	2515.8 (619.0)	698.8
Nasarawa	122.0 (56.1)	550.0 (246.1)	1100.1 (492.2)	305.6
Abuja (FCT)	75.0 (73.2)	364.2 (381.5)	728.4 (762.9)	202.3
Niger	363.6 (68.3)	1459.9 (255.4)	2919.8 (510.8)	811.1
Kwara	130.9 (24.6)	573.4 (248.8)	1146.8 (497.6)	318.6
Kogi	230.5 (74.6)	848.2 (169.9)	1696.3 (339.8)	471.2
Benue	120.5 (18.6)	582.2 (284.8)	1164.5 (569.6)	323.5
Oyo	183.6 (48.9)	635.4 (120.2)	1270.9 (240.3)	353.0
Osun	91.5 (58.0)	421.5 (202.2)	842.9 (404.4)	234.1
Ekiti	144.4 (33.2)	607.9 (239.6)	1215.8 (479.1)	337.7
Ondo	159.9 (50.6)	1006.8 (296.8)	2013.6 (593.6)	559.3
Ogun	227.9 (110.5)	927.1 (353.6)	1854.2 (707.3)	515.1
Lagos	81.4 (29.3)	426.9 (145.2)	853.9 (290.4)	237.2
Ebonyi	35.1 (25.9)	171.8 (134.6)	343.6 (269.2)	95.4
Enugu	78.6 (13.3)	322.9 (44.9)	645.8 (89.7)	179.4
Anambra	40.4 (3.5)	203.8 (24.2)	407.7 (48.4)	113.3
Imo	84.4 (32.9)	361.9 (79.7)	723.9 (159.3)	201.1
Abia	67.1 (13.9)	216.3 (38.4)	432.6 (76.8)	120.2
Edo	65.4	252.0	504.0	140

	(23.9)	(73.3)	(146.6)	
Delta	90.1 (7.8)	422.7 (66.0)	845.4 (132.1)	234.8
Bayelsa	32.2 (16.5)	106.9 (60.5)	213.8 (121.0)	59.4
Rivers	85.2 (54.4)	216.0 (34.5)	432.0 (69.0)	120
Akwa-Ibom	61.1 (10.4)	179.5 (33.9)	359.0 (67.8)	99.7
Cross River	87.3 (28.5)	472.7 (244.7)	945.3 (489.3)	262.6

Variable	**Measurement Unit**
Mean Estimate of Land Area for Cultivation	Thousand Hectares
Mean Maize Biomass Residue Potential	Thousand Tons
Mean Renewable Energy Potential	Gigajoule
Baseload Electricity Potential	Megawatt Hour
1 Gigajoule = 0.2778MWh	

Source: Koopmans and Koppejan (1997)

In this analysis, the main attribute is mean cost per unit land area ($\hat{C}$) and the complementary attribute is the mean productivity per unit land ($\dot{P}$). We introduce the following notations:

l = index of attribute layers, where $l = 1, 2, ..., L$

i= index of states, where i=1, 2, ..., n

r_{li} = attribute value in layer l of area i

For this analysis, an attribute value is the mean value of productivity per unit land ($\dot{P}$), and mean cost per unit land area ($\hat{C}$). Once values are derived for areas across an attribute layer, the relative suitability can then be determined. Given the previous notation, relative suitability, S_i, can be mathematically specified as follows:

$$S_i = \sum_{l} \hat{C}_l/\dot{P}_{li} \qquad (2.2)$$

Equation (2.2) represents a simple division of the mean values derived for each attribute. MCCPRI is a suitability score, giving a composite suitability layer. An Excel spreadsheet for data input and manipulation and GIS, a visualization tool, are employed. It is assumed that crop residues have utilization potential in five broad categories namely: re-plowing into the soil to enrich the soil, domestic uses by farming communities, agricultural uses such as livestock feed, feedstock for renewable biomass-fired electric power generation, and other industrial uses. Assuming equi-proportional utilization across these five categories, then only 20% (one-fifth) of available residues will be harnessed for biomass baseload electricity generation.

This study will attempt to identify those areas of relatively high suitability based on which production economic analyses can be performed. Economists do not pose to be omniscient, but rather help to provide appropriate incentives for entrepreneurs (Schwarz, 2017). Designing such incentives advances alternatives, based on estimated risks and returns. Recall, as earlier mentioned, initiatives that increase energy choices and promote adaptability to change can potentially result in cost-effective biogas and biomass technology markets in Nigeria (Energy Commission of Nigeria, 2012). In recent years, thinking of incentives as part of a system of interrelated instruments and influences has been a major advance in the economics of incentives (Holmström, 2017).

Therefore, we employ a residue product ratio (RPR) from past studies and published reports. Residue product ratio is the amount of crop residue available per unit amount of crop harvest. This study uses an RPR of 2.5 based on published reports (Koopmans, 1997). Appendix 8 show values of agro-ecological variables and productivity indexes in different states. For cost per unit land, a low value is desirable. On the contrary, high values are desirable for productivity per unit land. Thus, MCCPRI factors with lower values are desirable for facility siting in comparison to siting in states with higher composite values. That is, a lower cost per unit land area in combination with a higher crop harvest per unit land area is desirable.

2.4 Results and Discussions

Data processing using Excel and GIS reveal the relative suitability of different states in Nigeria for maize feedstock-based biomass-fired electric power generation. By using human judgment and descriptive statistics, this analysis categorizes suitability into 12 categories to obtain the most suitable state. Delta and Gombe states constitute the line up in the next best category. Sokoto, Yobe, and Kogi states constitute the line up in the third category of relative suitability. Seemingly, the decision of the NNPC to sign a memorandum of understanding (MoU) with the government of Kogi State to locate a biomass power plant in Kogi appears to be appropriate.

State level perspective of linkages between spatial energy systems and economic activities better captures local conditions, dynamics and effects of energy and environmental economics learning, adaptation, and development. Technology deployment plans of public agencies and industrial entities at all jurisdictional levels for energy development is essential to the operation of society (Inyang, 2006). Direct implementation of sustainable energy systems is more promising on a regionalized basis. Policy discussions disconnected from contextual realities of social infrastructure results in delays and lags of technology adoption thereby potentiating failure.

NIIMP acknowledges the place of social infrastructure to realize meaningful socio-economic development. The reason is that understanding the dynamics of organizational local environments in terms of political climate and resource availability is vital for successful policy implementation. Social and political-economy realities in Nigeria leads to state level analyses as state Governors act like Chief Executive Officers (Balta-Ozkan et al., 2015; Guo et al., 2016; Mullins et al., 2014; Wang and Huang, 2016; National Planning Commission, 2015). States areas identified as having relatively high suitability are an indication of low risk and high returns based on availability of biomass feedstock for plant operations.

Nigeria has 36 states and Abuja as the seat of administrative power. This research focuses on cost of maize production because that is the core motivation for cultivation of maize in Nigeria. Residues that serve as biomass feedstock are by-products of harvesting and processing of maize cobs.

Nigeria Showing Cost of Maize Production Per Unit Land Area

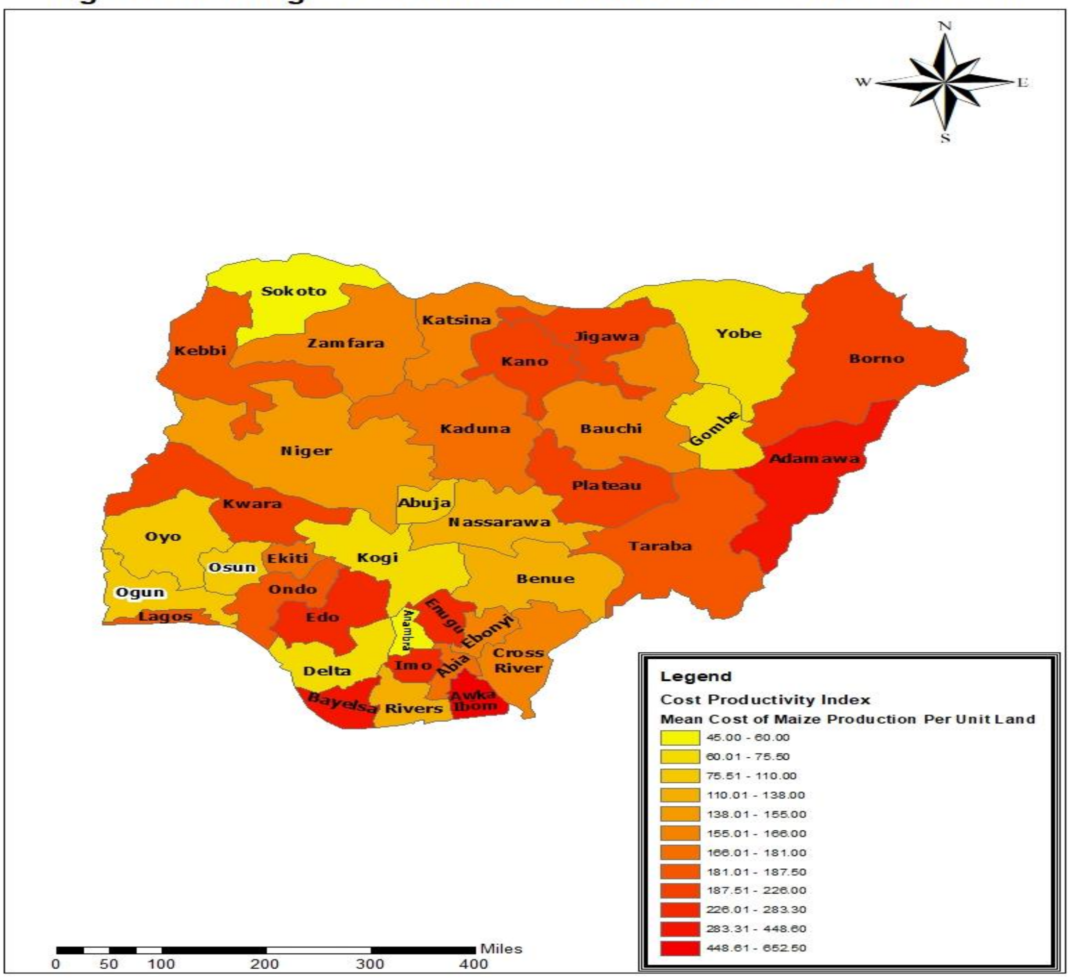

Figure 2.1: Factor Map of Nigeria Showing Mean Cost of Maize Production Per Unit Land (Naira/ha-yr)

Lower cost per hectare is desirable. Figure 2.1 presents results showing Sokoto state in the north-west Agro-Ecological Zone as the best location based on the mean cost of maize production criterion.

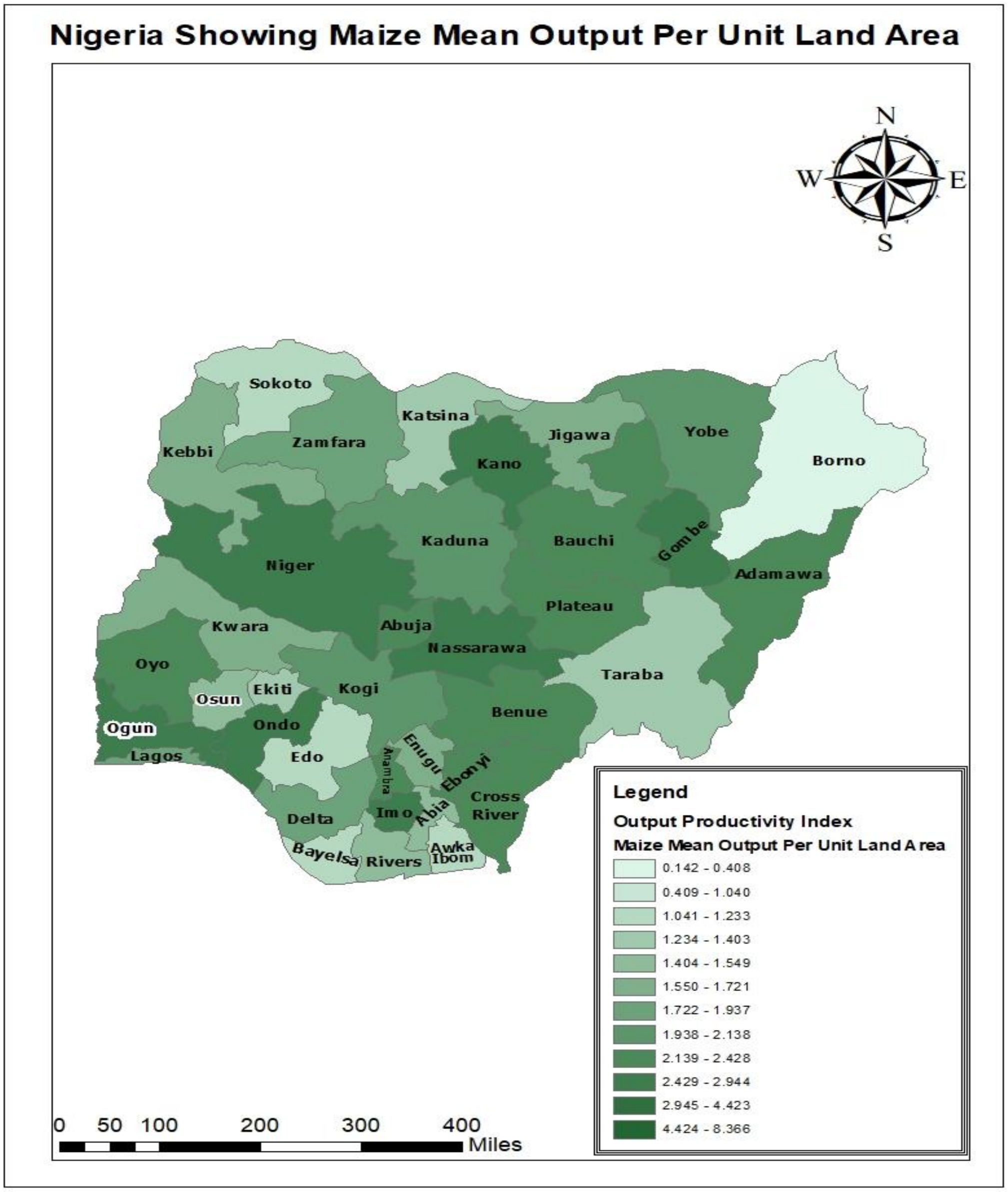

Figure 2.2: Factor Map of Nigeria Showing Mean Maize Harvest per Unit Land (Tons/ha-yr)

High values of crop harvest per unit land is desirable. Considering output per unit land area criterion or factor, Figure 2.2 show Ondo state in the south west Agro-Ecological Zone qualifies as the best site for biomass power plant siting.

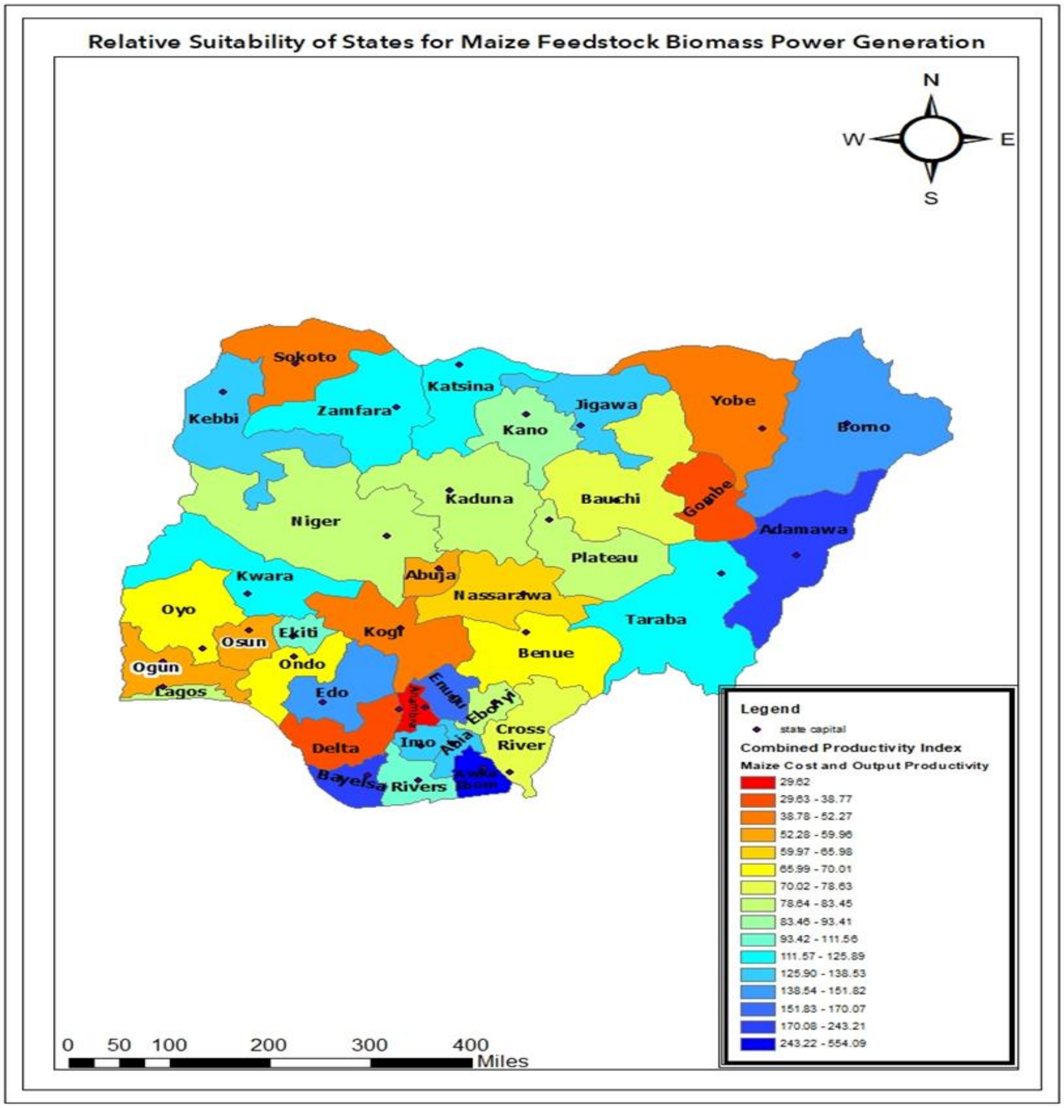

Figure 2.3: Chloropleth Map Showing Relative Suitability of States for Maize Residue-Based Biomass-Fired Electric Power Generation Based on Cost and Land Use Productivity (Naira/ton)

Based on the composite productivity factor, Anambra state in the south east agro-ecological zone comes out on top (see Figure 2.3). Therefore, there is the possibility that if a Relative Suitability Analysis was done, then NNPC might have signed such an MoU with at least three other states (Gombe, Delta, and Anambra) thereby taking advantage of economies of scale. It is worthy of note that Anambra state as the best suitable site for biomass power generation will have remarkable consequences for air pollution when compared with any fossil fuel alternative. A study conducted on air pollution levels in cities across the globe identified Onitsha, a city in Anambra state among the 20 worst cities worldwide for air pollution (McCarthy, 2016).

These 20 cities have the highest levels of small and fine particulate pollution (PM_{10} and $PM_{2.5}$). Onitsha has the highest levels of PM_{10} worldwide, where it reaches almost 30 times the recommended level. Ambient outdoor air pollution is the greatest environmental risk to health with an estimated 4.3 million people dying prematurely annually (Ritchie and Roser, 2018). Major shifts in preferences, cost efficiency, service quality improvements, simultaneous mitigation of adverse environmental and human health impacts are core to sustainability (Church and Murray, 2009). Air pollution is linked to 1.4million deaths from stroke, 2.4 million deaths due to heart diseases, and 1.8 million deaths due to lung disease and cancer, annually (World Health Organization, 2018).

Real and perceived risks of long-term and short-term environmental degradation, accidents, and human health damages are the primary driving factors in energy acceptability. Thus, these health damage and death figures have implications for energy acceptability which is defined as the liability of energy sources to be produced, transmitted, and used in manners that preserve the environment and enjoy public acceptance (Inyang, 2006). Burning of fossil fuels like coal are linked to air pollution and a higher number of deaths per unit electricity consumed when compared with biomass-fired (Wagner, 2018).

Therefore, biomass-fired baseload electricity generation has zero net gain in CO_2 emissions and is a welcome development in Anambra state. In the final analysis, only the south western agro-ecological zone is not in the topmost three relative suitability categories based on this combined productivity index; at least for maize feedstock. Thus, the National Productivity Center should make efforts in line with the APP for improvements in maize cultivation management practices in the south western part of Nigeria towards improved crop yield productivity and an increased chance of biomass power development.

2.5 Conclusions

Productivity improvement is one of the three central themes of Nigeria's APP. In Nigeria, reliable data from published reports on Wet Season Agricultural Performance Surveys (WSAPS) reveal Anambra state as relatively the most desirable location based on maize feedstock land use and cost productivity indexes. Spatial location and suitability analyses are key to developing a sustainable energy system. Suitability analysis presents an opportunity for real-world application for siting renewable electric power generation facilities. This analysis is in alignment with the NIPR and APP drive to improve productivity. Power sector stakeholders in Nigeria should take advantage of this kind of business site location analysis technique when making decisions of energy infrastructure development; in this case, biomass power plant for baseload generation.

CHAPTER 3: POWER PLANT LOCATION-ALLOCATION OPTIMIZATION

3.1 **Spatial Optimization and Location Allocation in the Nigerian Power Sector**

The application of spatial optimization to energy systems modelling is an emerging field and the continual deployment of spatial optimization is vital to optimal exploitation of untapped renewable energy resources to stir economic growth in Nigeria. The Power Holding Company of Nigeria (PHCN) uses spatial optimization in the management of electricity supply facilities for its clientele base. PHCN employs geometric and attributes data in locating, mapping, and monitoring facilities and service quality, and for spatial analysis throughout the generation, transmission, and distribution spectrum of the nation's power grid (Matthew et al., 2017; Merem et al., 2017; Resch et al., 2014).

Location-allocation models are popular when siting bio-energy facilities as well as modelling and decision making. An integrated model in the literature combining multi-criteria inclusion-exclusion analysis and facility location-allocation finds application for suitability analysis and optimal siting of biogas plants. Results of a study in Ohio (Sahoo et al., 2018), of integrated model application on sustainability of feedstock supply estimates availability of 4 – 13 dry Tera gram (Tg) of crop residues to install 1–25 regional biogas plants with feedstock capacities ranging from 10 to 1000 dry Gigagram (Gg).

Location-allocation problem solving is of interest to both private and public sectors of an economy. Economics involves allocating scarce resources to make ends meet. In this part of the research, a multi-state siting for biomass power generation in Nigeria is performed. In addition to Anambra state which is the best optimal site, the survey area incorporates the "next best" two categories of relative suitability which includes Delta, Gombe, Kogi, Sokoto, and Yobe states. This analysis is based on the method known as Location Allocation Modelling described in Chapter 12 of *Business Site Location Analysis* (Church and Murray, 2009).

3.2 Optimizing Accessibility as an Efficiency Measure in Siting a Power Generation Facility

This research investigates a multi-site location-allocation problem (Church and Murray, 2009). Location-allocation modelling builds on the results of suitability analysis to identify the most suitable locations based on spatial distribution of biomass feedstock resources and their renewable energy potential. Mathematical specification in location modelling requires as a matter of priority that we decide on a measure of efficiency that we seek to optimize. Power plants are in the category of public-service facilities. Accessibility to user populations, a key indicator of energy sustainability, influences siting decisions, especially in Nigeria where transmission infrastructure is a concern to stakeholders.

Energy availability, acceptability, and accessibility are the three main indices of energy sustainability (Inyang, 2006). Transmission is a major concern in the Nigeria power infrastructure as transmission capacity is currently below 10,000 MW. In other words, even if generation capacity improves tremendously there is the possibility that transmission concerns may limit production efficiency through constrained transmission. Biomass power, being a renewable baseload electricity sources utilizes existing transmission capacity efficiently due to their high capacity factors (Matek and Gawell, 2015).

The planning process for expansion of transmission capacity must aim at reduction in transmission losses, and improvements in ease of connectivity to planned power generation facility sites (National Planning Commission, 2015). Recently in February 2018, the World Bank officially gave an International Development Association (IDA) grant of about $486 million for rehabilitation and upgrading of Nigeria's electricity transmission lines and sub-station infrastructure (The World Bank, 2018a). The purpose of the investments that fall under the Nigeria Electricity Transmission Project are targeted at increasing the power transfer capacity of Nigeria's transmission network and aiding electricity distribution companies in supplying consumers with additional power.

Together with other investments and policy measures, the project will contribute to ensuring adequate and reliable electricity supply that is necessary for Nigeria's continued economic development. It will also support private sector participation, capacity development and better governance in the Transmission Company of Nigeria and sector institutions. Investments are known to increase a country's competitive strength substantially and sustainably; especially in a country like Nigeria with a relatively low base (National Planning Commission, 2015). Daily total constrained electric power is a key performance indicator for the Nigerian Electricity Regulatory Commission (NERC).

Constrained daily electricity in Nigeria currently stands at over 1,000 MW (see Appendix 7). Constrained electric power reflects underutilization of the nation's generating capacity, referring to available power not generated due to factors like: limited supply of generation fuel such as gas, transmission constraint, and demand load (Olatomiwa et al., 2015). Energy planning based on scenarios of energy demand, energy mix, and costs constitute the key aspects of Nigeria Energy Calculator (NECAL) 2050, an Energy and Environment Analysis Tool of the Energy Commission of Nigeria (ECN). The measure of efficiency in the configuration of a power plant facility is the total distance between each demand area (which is represented by center point of the states) to its closest neighboring facility multiplied by the "State electricity supply deficit per thousand persons" as proxy for electricity demand being supplied from generation site to demand area locations (see Appendix 4).

The distance to the nearest power generation facility is a determinant of electricity consumption in Nigeria (Ubani, 2013). The *p*-median problem is employed here to site biomass power plants by recognizing the best multi-state facility siting configuration (that is, facility location spatial distribution) and allocation. We measure distance as a Euclidean distance measure. The decision is whether a potential biomass power plant site j is selected, Y_j, and to determine which power plant site serves a state i, X_{ij}. It is assumed that the relative cost of construction and operation of a biomass power plant is the same across these demand areas.

Budgetary constraints will limit number of power plant facilities that can be sited. The number of p values are varied, and the way accessibility fluctuates relative to p values is measured. Input data notations include:

i. Index of demand areas, i, where $i = 1, 2, 3, \ldots., n$.

ii. Index of potential facility sites, j, where $j = 1, 2, 3, \ldots., m$.

iii. Shortest distance from demand area i to potential facility site j, d_{ij}

iv. Quantity of electricity demand proxied by state supply deficit per thousand persons, q

v. Number of facilities to be located, p

We proceed with formulation as follows:

Y_j = {1, if facility at site j is located; 0, otherwise}

X_{ij} = {1, if demand *i* is served by facility *j*; 0, otherwise}

3.3 **Methodology**

The efficiency between any demand area *i* and a biomass power plant located at site *j* is calculated as follows:

$$q_i \, d_{ij} \tag{3.1}$$

That is, the transmission distance required to transport available energy from a potential generation site to a demand area, d_{ij}, is multiplied by the total demand in area *i*, q_i, proxied by the state supply deficit per thousand persons. This research assumes zero transport cost from residue supply areas to the power plant potential site. By incorporating the allocation decision which indicates which power plant serves which demand area, the following weighted assignment distance can be obtained:

$$q_i \, d_{ij} \, X_{ij} \tag{3.2}$$

X_{ij} =1 when demand area *i* is served by a power plant located at site *j* in (3.2). The result is the product of transmission distance from potential generation site to demand area, d_{ij}, multiplied by the total demand in area *i*, q_i, proxied by the state supply deficit per thousand persons. This value is summed across all potential biomass power plants and all demand areas as follows:

$$\text{Minimize} \quad \sum_{i=1}^{n} \sum_{j=1}^{m} q_i \, d_{ij} \, X_{ij} \tag{3.3}$$

Equation (3.3) is a system efficiency measure, corresponding to total weighted transmission distance associated with an allocation, X_{ij}. Optimization of this accessibility measure is the aim of this research. Logistical, natural resource, and technical factors form a complex web of determinants of accessibility of different types of energy resources in a country or region (Inyang, 2006). One constraint is that each demand area is allocated to a power plant, that is, each demand area must be served. Consequently, the demand area *i*, can be specified as follows:

$$\sum_{j=1}^{m} Xij = 1 \qquad (3.4)$$

When allocating demand areas to power plants, there must be no allocation unless a power plant is sited. The inequality for demand area *i* and facility *j* is employed to specify mathematically as follows:

$$X_{ij} \leq Y_j \qquad (3.5)$$

Allocation assignment is possible when $Y_j = 1$, then X_{ij} may be equal either zero or one. Otherwise, X_{ij} must be zero when $Y_j = 0$ due to the zero bound on the inequality's right-hand side. Thus, Y_j is a binary variable. The specific number of power plants to be sited, *p*, can be calculated mathematically as follows:

$$\sum_{j=1}^{m} Yj = p \qquad (3.6)$$

Due to binary nature of Y_j, equation (3.6) guarantees that exactly *p* of the Y_j variables will equal one. The number of located facilities can be varied to see how optimization solution changes. Therefore, the location-allocation model can be specified as follows:

$$\text{Minimize} \quad \sum_{i=1}^{n} \sum_{j=1}^{m} q_i \, d_{ij} \, X_{ij} \qquad (3.7)$$

This is the measure to be optimized. The objective function seeks to minimize total weighted assignment transmission distance, subject to:

$$\sum_{j=1}^{m} X_{ij} = 1 \qquad \text{for each } i = 1, 2, \ldots, n \qquad (3.8)$$

$$X_{ij} \leq Y_j \qquad \text{for each } i = 1, 2, \ldots, n \text{ and } j = 1, 2, \ldots, m \qquad (3.9)$$

$$\sum_{j=1}^{m} Y_j = p \qquad (3.10)$$

$$Y_j = \{0,1\} \text{ for each } j = 1, 2, \ldots, m$$

$$X_{ij} = \{0,1\} \text{ for each } i = 1, 2, \ldots, n \text{ and } j = 1, 2, \ldots, m \qquad (3.11)$$

Constraints *(3.8)* are allocation conditions that require each demand area *i* to have its demand supplied by a facility. Constraints *(3.9)* restrict allocations for a specific demand *i* to only sites *j* selected to house a biomass power plant. The minimization objective and constraints *(3.8)* and *(3.9)* ensures that allocation of each demand is to the closest facility. Constraints *(3.10)* specifies the number of *p* sites designated for facility placement. Binary requirements are imposed on Constraint *(3.11)*. Thus, the location-allocation model solves a *p*-median problem, which is an integer-linear programming problem (Church and Murray, 2009).

The commercial software package, LINGO, is employed in this study. In this study, modelling is applied to the six suitable states mentioned earlier. The study attempts to site three facilities, that is, $p = 3$. We randomly choose 3 to show a simplified multi siting decision. Later, this analysis will examine lower and higher number of siting decisions. There are six states and seven potential biomass electric power generation sites with varying demands as proxied by "State supply deficit per thousand persons" (see Table 3.1 below). For a simplified analysis, we plan to have one potential site in each state except for the best relative suitability state where we decide to have two potential sites.

Thus, there are seven potential sites. Note that letters A – F in the mathematical formulation represents Anambra, Delta, Gombe, Kogi, Yobe, and Sokoto states, respectively, as demand areas. The per capita electricity supply deficit in each state (measured in MW/per ten thousand persons) is denoted as q_i. To have a point of target LGA to supply in those states, the state capitals were chosen, that is, the administrative seat of state government. Being that Onitsha spreads over two LGAs (namely, Onitsha North and Onitsha South), we select these two LGAs in Anambra state as potential sites. Expectations are that longer distances are associated with higher transmission costs.

Essentially, the study investigates a cost minimization problem. Thus, the analysis goes beyond just generation to considerations of transmission. The Nigerian integrated infrastructure master plan (NIIMP) considers electric power generation and transmission capacity expansion as a priority for national development (National Planning Commission, 2015). This model has seven siting decision variables and 42 allocation decision variables. The coefficients are product of distance of transporting available energy and the State supply deficit per thousand persons. The model also has six allocation constraints, 42 constraints limiting assignment to open facilities and one constraint that specifies the number of facilities to be sited (p = 3).

Model structure depicts a mixed integer linear programming problem (MILP) as all expressions are linear, and a subset of the variables is restricted to integer values. The problem is specified using LINGO (see Appendix 11). Model description shows sets for demand, sites and allocations (representing all possible demand-site assignments).

Table 3.1: Demand and Distance Information

		Potential Sites						
Demand Area	q_i	Onitsha North (X_1) (miles)	Onitsha South (X_2) (miles)	Asaba (X_3) (miles)	Gombe (X_4) (miles)	Lokoja (X_5) (miles)	Damaturu (X_6) (miles)	Sokoto North (X_7) (miles)
Anambra (A)	111	15.7	18.3	21.6	395.6	107.1	507.5	480
Delta (B)	221	75.9	73.3	71.8	485.9	167	596.6	518.4
Gombe (C)	36	413.7	416.3	414.1	3.4	346.4	116.6	442.1
Kogi (D)	139	121.5	123.1	117.9	352	12.9	452.6	363.6
Yobe (E)	13	533.9	536.4	536.1	139.1	454.2	35.1	439.2
Sokoto (F)	78	484.4	485.8	480	442.9	373.3	461.6	2.9

Source: (Shonibare, 2014, Distance World, 2017, Church and Murray, 2009)

Algebraic specification of p-median is as follows:

Minimize $1743X_{A1} + 2031X_{A2} + 2398X_{A3} + 43912X_{A4} + 11888X_{A5} + 56333X_{A6} + 53280X_{A7} + 16774X_{B1} + 16199X_{B2} + 15868X_{B3} + 107384X_{B4} + 36907X_{B5} + 131849X_{B6} +$

$114566X_{B7} + 14893X_{C1} + 14987X_{C2} + 14908X_{C3} + 122X_{C4} + 12470X_{C5} + 4198X_{C6} + 15916X_{C7} + 16889X_{D1} + 17111X_{D2} + 16388X_{D3} + 48928X_{D4} + 1793X_{D5} + 62911X_{D6} + 50540X_{D7} + 6941X_{E1} + 6973X_{E2} + 6969X_{E3} + 1808X_{E4} + 5905X_{E5} + 456X_{E6} + 5709X_{E7} + 37783X_{F1} + 37892X_{F2} + 37440X_{F3} + 34546X_{F4} + 29117X_{F5} + 36005X_{F6} + 226X_{F7}$

Subject *to:*

$$X_{A1} + X_{A2} + X_{A3} + X_{A4} + X_{A5} + X_{A6} + X_{A7} = 1$$

$$X_{B1} + X_{B2} + X_{B3} + X_{B4} + X_{B5} + X_{B6} + X_{B7} = 1$$

$$X_{C1} + X_{C2} + X_{C3} + X_{C4} + X_{C5} + X_{C6} + X_{C7} = 1$$

$$X_{D1} + X_{D2} + X_{D3} + X_{D4} + X_{D5} + X_{D6} + X_{D7} = 1$$

$$X_{E1} + X_{E2} + X_{E3} + X_{E4} + X_{E5} + X_{E6} + X_{E7} = 1$$

$$X_{F1} + X_{F2} + X_{F3} + X_{F4} + X_{F5} + X_{F6} + X_{F7} = 1$$

$X_{A1} \leq Y_1$, $X_{A2} \leq Y_2$, $X_{A3} \leq Y_3$, $X_{A4} \leq Y_4$, $X_{A5} \leq Y_5$, $X_{A6} \leq Y_6$, $X_{A7} \leq Y_7$, $X_{B1} \leq Y_1$, $X_{B2} \leq Y_2$, $X_{B3} \leq Y_3$, $X_{B4} \leq Y_4$, $X_{B5} \leq Y_5$, $X_{B6} \leq Y_6$, $X_{B7} \leq Y_7$, $X_{C1} \leq Y_1$, $X_{C2} \leq Y_2$, $X_{C3} \leq Y_3$, $X_{C4} \leq Y_4$, $X_{C5} \leq Y_5$, $X_{C6} \leq Y_6$, $X_{C7} \leq Y_7$, $X_{D1} \leq Y_1$, $X_{D2} \leq Y_2$, $X_{D3} \leq Y_3$, $X_{D4} \leq Y_4$, $X_{D5} \leq Y_5$, $X_{D6} \leq Y_6$, $X_{D7} \leq Y_7$, $X_{E1} \leq Y_1$, $X_{E2} \leq Y_2$, $X_{E3} \leq Y_3$, $X_{E4} \leq Y_4$, $X_{E5} \leq Y_5$, $X_{E6} \leq Y_6$, $X_{E7} \leq Y_7$, $X_{F1} \leq Y_1$, $X_{F2} \leq Y_2$, $X_{F3} \leq Y_3$, $X_{F4} \leq Y_4$, $X_{F5} \leq Y_5$, $X_{F6} \leq Y_6$, $X_{F7} \leq Y_7$

$Y_1 + Y_2 + Y_3 + Y_4 + Y_5 + Y_6 + Y_7 = 3$

$Y_1 = \{0,1\}$, $Y_2 = \{0,1\}$, $Y_3 = \{0,1\}$, $Y_4 = \{0,1\}$, $Y_5 = \{0,1\}$, $Y_6 = \{0,1\}$, $Y_7 = \{0,1\}$

$0 \leq X_{ij} \leq 1$ *for all i, j*

Model structure follows the structure of an algebraic statement. Data specification for the model is at the bottom of the LINGO file.

3.4 Results and Discussions

Results from location-allocation optimization identifies Asaba (Y3) in Delta state, Lokoja (Y5) in Kogi state, and Sokoto (Y7) in Sokoto state, as optimal locations among the topmost three categories of relative suitability agro-ecological zones. The importance of multi-state siting is in the fact that a close look at the electricity distribution coverage areas in Nigeria (Abanihi et al., 2018; Shonibare, 2014) reveals there are distribution company owners whose multi-state coverage (see Figure 3.1) crosses the borders of the six agro-ecological zone (see the "Per Capita Electricity Supply" and "Per Capita Electricity Supply Deficit" in Appendix 4).

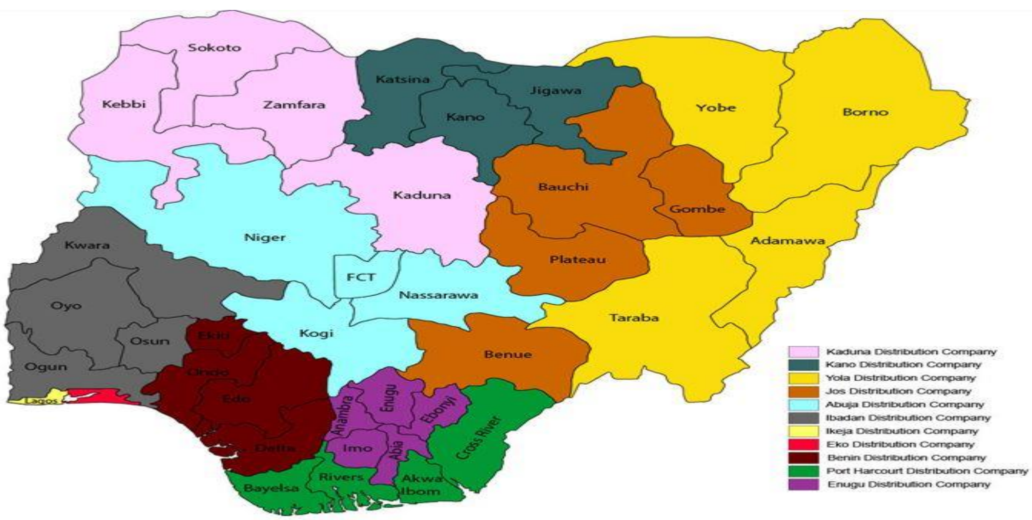

Figure 3.1: Multi-State Electricity Distribution Coverage **Source**: International Energy Agency (2014)

We regard the remaining four as sub-optimal locations/variables. From the output, there is a global optimal solution. Such utility companies in a bid to take advantage of economies of scale are more likely to want to site more than one facility simultaneously in a coverage area with variation in relative suitability across space. Therefore, it is vital to know how the other potential sites among the "next best" set of relative suitability categories perform as optimal sites. Figure 3.2 shows the demand areas in the topmost three categories of relative suitability with color distinction according to relative suitability as all the other categories are merged into one being depicted by the white color.

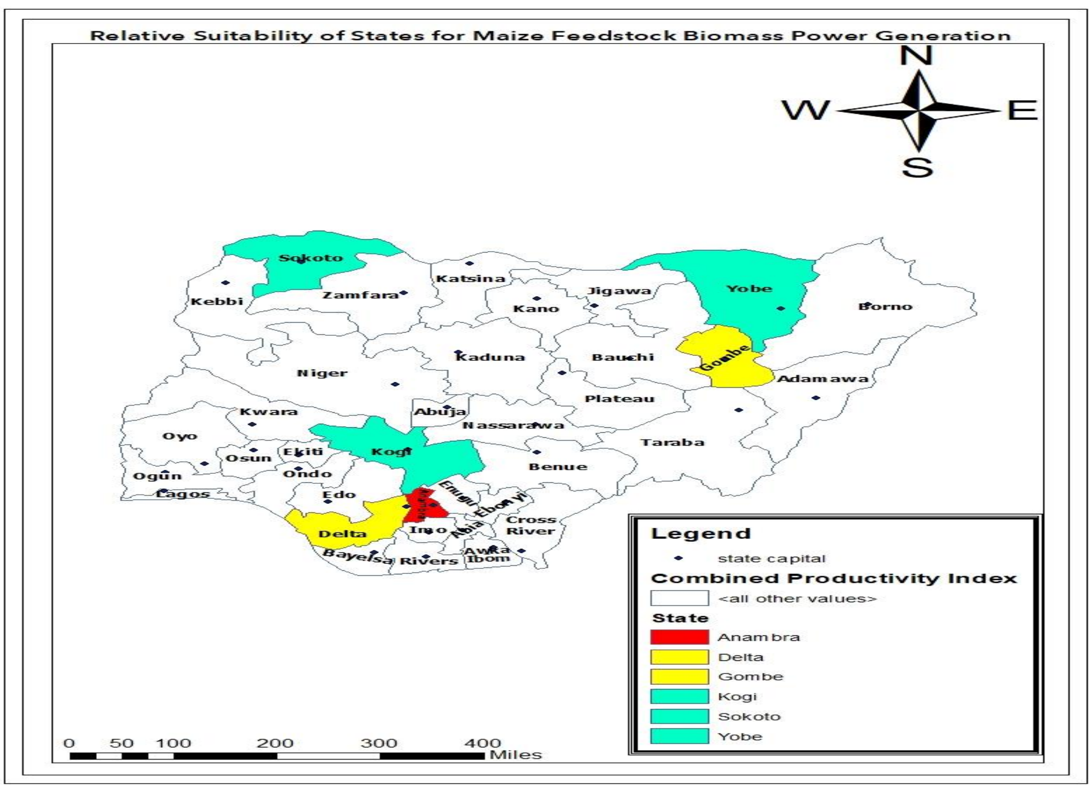

Figure 3.2: Map Showing States in Top Most Three Relative Suitability Categories

Solution reports showing details of the optimization model when *p* varies from 1-5 is in Appendix 12. When LINGO has a solution to a linear optimization model, then there is a definitive best solution which is called the global optimum. However, multiple optima may exist. The interpretation of global optimal solution is that a feasible solution exists with an objective value that is at least as good as or even better any other feasible solutions to the model. A globally optimal solution is an attribute common with linear models. A close look at the solution report of the MILP model shows an objective value for the weighted assignment transmission distance to be equal to 4,562,998 MW-miles.

Recall that distance (measured in miles) was weighted with per capita electricity supply deficit (measured in MW). Optimal locations namely: Asaba (Y3) in Delta state, Lokoja (Y5) in Kogi state, and Sokoto (Y7) in Sokoto state all have a reduced cost of zero and a variable coefficient value of one. Reduced cost signifies opportunity cost. Reduced cost is the change in the objective function if any of those sub-optimal variables (that is, potential sites) are required, assuming a feasible solution still exists, to be equal to (or greater than) one as with the optimal variable coefficients. In other words, the reduced/opportunity cost of each of the decision variables in the model is the rate at which the cost minimization objective value worsens, that is increases, for a unit change in the optimized value of any of those decision variables, all other things remaining the same. Appendix 9 presents results in greater detail.

The transmission distances to transport available energy from the three optimal sites identified to all the demand areas are specified after a total of 119 iterations. The solution report also shows us which constraints are binding, that is, those constraints that have values satisfying the optimal solution. Any change in the value of such constraints alters the optimal solution. Binding constraints are associated with zero slack or surplus value. Furthermore, dual prices can only be positive when a constraint is binding. Dual prices indicate the improvement in the objective function provided the constraint is relaxed by one unit.

How does the objective value change as more than, or less than, three facilities are sited in the same coverage area of the topmost three categories of relative suitability, that is, when p = 1, 2, 4, or 5. The scripts for the LINGO command remain essentially the same except that p now changes from 3 to optimization instances where p = 1, 2, 4, or 5. The mathematical statements are adjusted in accordance ($Y_1 + Y_2 + Y_3 + Y_4 + Y_5 + Y_6 + Y_7 = 1$; $Y_1 + Y_2 + Y_3 + Y_4 + Y_5 + Y_6 + Y_7 = 2$; $Y_1 + Y_2 + Y_3 + Y_4 + Y_5 + Y_6 + Y_7 = 4$; *and* $Y_1 + Y_2 + Y_3 + Y_4 + Y_5 + Y_6 + Y_7 = 5$). Solution reports for varying numbers of power plants from 1 to 5 are in Appendix 12.

Table 3.2 presents a summary of the optimal locations and the minimization objective value as the number of power plants varies over the three topmost relative suitability areas. Results show cumulative available renewable energy for utilization by power plants for electric power generation and the corresponding locations of those power plants in each scenario (see Appendix 8 for the contribution of each state in the potential renewable energy and electricity in table 3.2). The scenario with five power plants appears best with the least objective value from these minimization exercises by minimizing total cost associated with transmission of available energy.

Table 3.2: Summary of Sensitivity Analysis with Varying Number of Power Plants

p	Objective Value	Iterations	Elapsed runtime seconds	Optimal Plant Locations	Potential Total Renewable Energy, GJ and (Electricity, MW)
1	9598543	0	0.13	Y (3): Asaba	845.4 (9.8)
2	6679471	175	0.40	Y (3): Asaba Y (7): Sokoto North	1124.7 (13.02)
3	4562998	119	0.79	Y (3): Asaba Y (5): Lokoja Y (7): Sokoto North	2821.1 (32.7)
4	4067757	93	0.23	Y (3): Asaba Y (4): Lokoja Y (5): Gombe Y (7): Sokoto North	4149.5 (48.03)
5	3995052	42	0.13	Y (1): Onitsha North Y (3): Asaba Y (4): Lokoja Y (5): Gombe Y (7): Sokoto North	4557.2 (52.8)

Figure 3.3 and 3.4 are plots of a varying number of power plants with corresponding minimization objective values and available renewable energy for

electricity generation. Increasing number of plants in multi siting decisions is linked with reducing energy transmission distance and its associated cost while simultaneously increasing residue waste to energy utilization. Maize residues belong to solid wastes category known as “food and green” (World Bank, 2018). Food and green account for the largest share of global waste composition (see Figure 3.5) with Nigeria having a waste generation rate higher than China, Pakistan and Kenya.

Therefore, we can infer that a drive towards biomass siting in multiple locations presents opportunity for better optimal decision making than in single siting decision, all other conditions remaining the same.

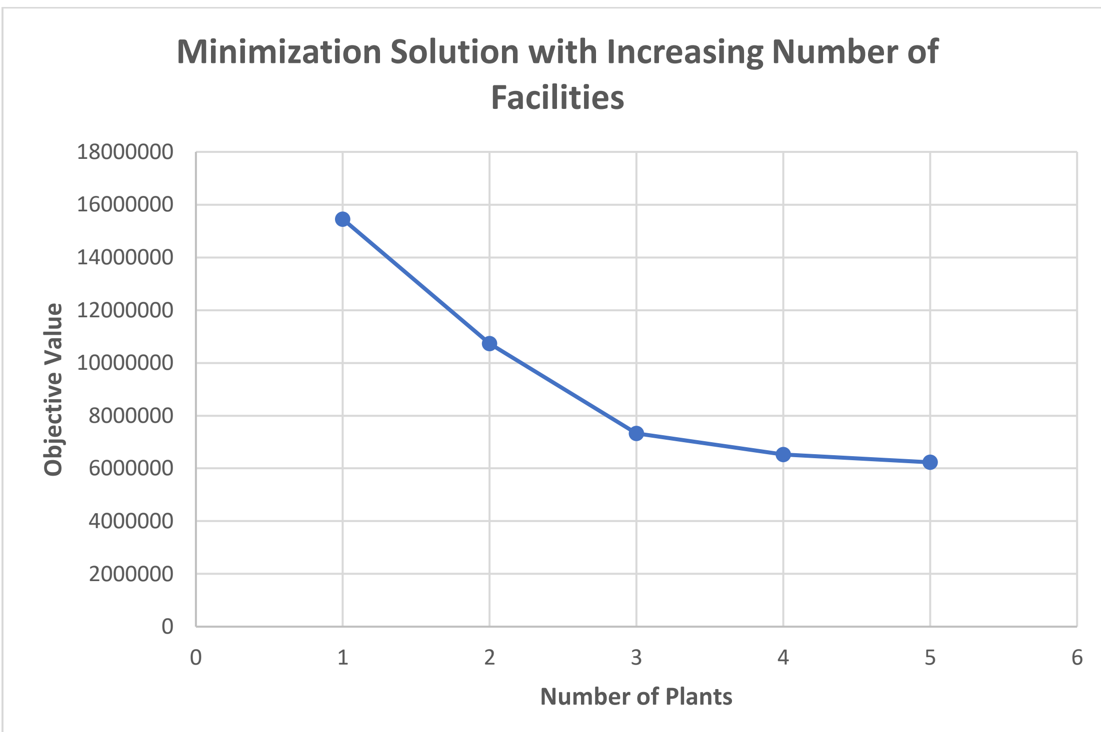

Figure 3.3: Minimization Objective and Varying Number of Power Plants

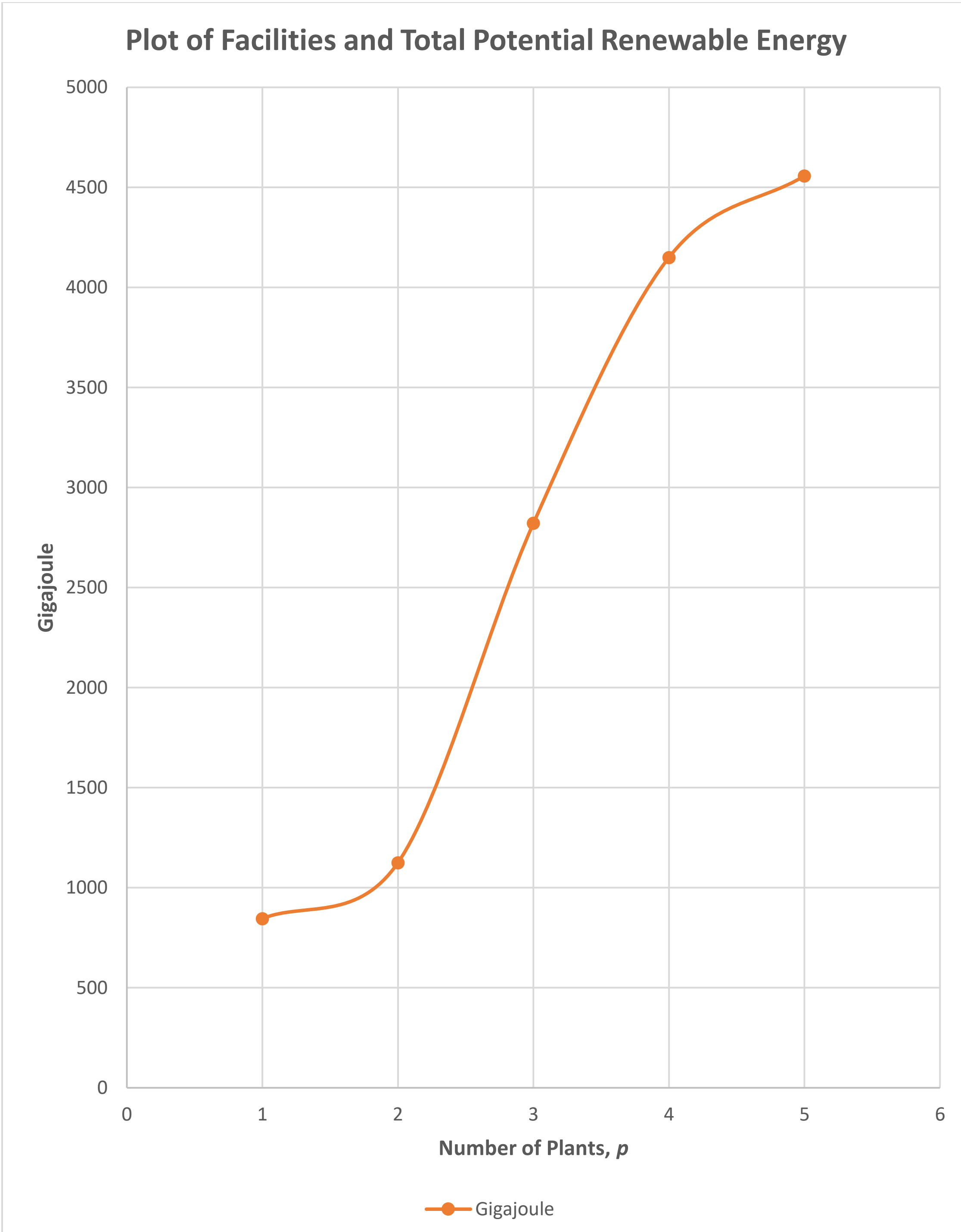

Figure 3.4: Renewable Energy Potential and Varying Number of Power Plants

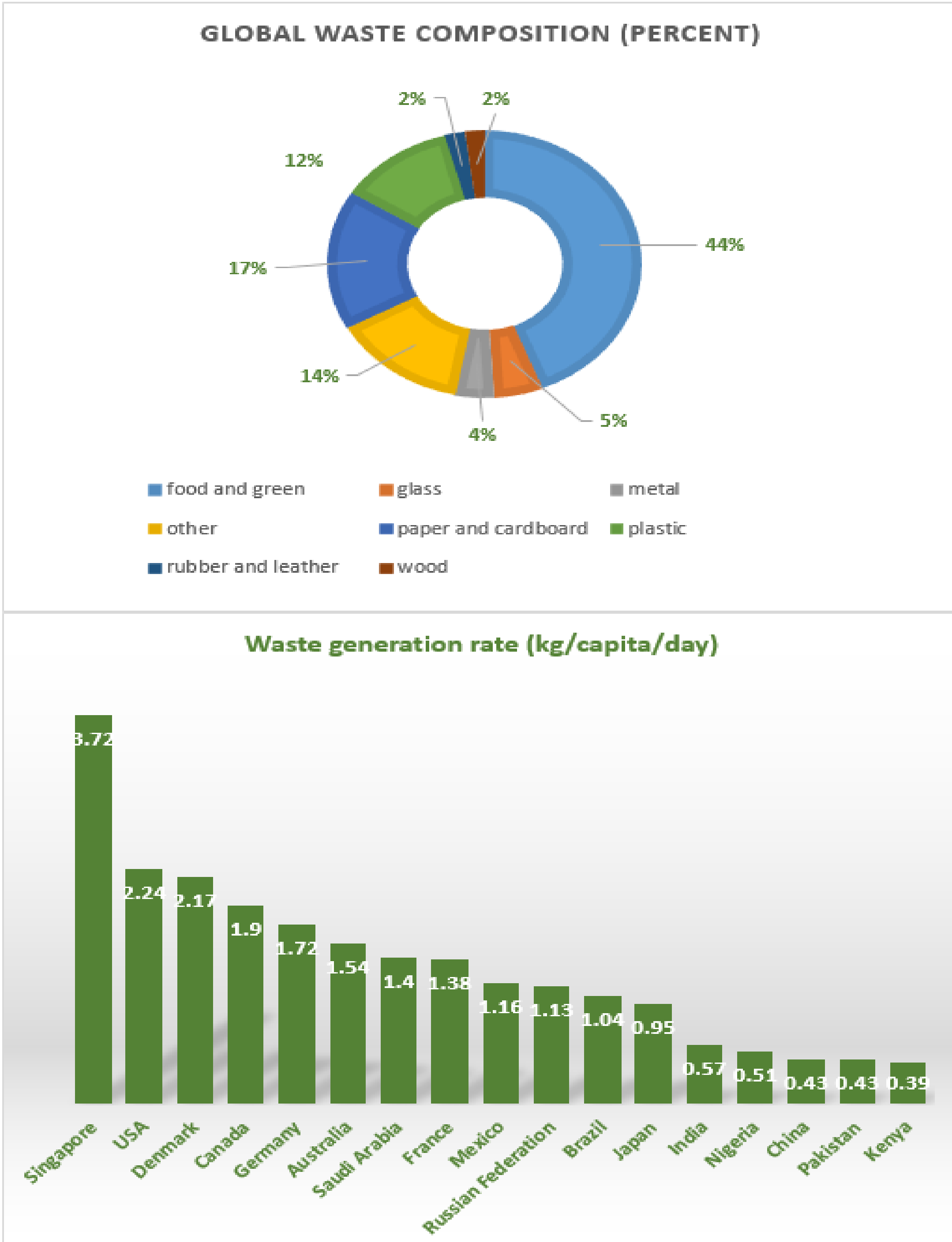

Figure 3.5: Global Waste Generation **Source:** Kaza et al. (2018)

Table 3.3 presents sales value salvaged by increasing number of biomass baseload electricity generation based on renewable energy potential in Appendix 8 (International Energy Agency, 2014). Availability of data on biomass power plant capital cost and operational costs at state level will make deeper analysis possible. However, data is lacking. The newly signed Memorandum of Understanding for the construction of biomass power plant in Kogi state does not provide any figures on the estimated capital costs and operational cost. Hence, inference on benefit cost analyses is limited only to estimated benefit values due to estimated sales values salvaged annually.

Recall that sales value lost is about $12.6 billion dollars due to a deficit of about 135,000MW electricity. Therefore, about $93,333.33 sales value lost is associated with 1 MW electricity deficit (assuming direct and linear relationship between salvage value and electricity supply).

Table 3.3: Sales Value Salvaged with Increasing Penetration of Biomass Baseload Power Plants

p	Objective Value	Optimal Plant Locations	Baseload Electricity (MW)	Cumulative Sales Value Salvaged (USD)
1	9598543	Y (3): Asaba	9.8	914,666.34
2	6679471	Y (3): Asaba Y (7): Sokoto North	13.02	1,215,199.57
3	4562998	Y (3): Asaba Y (5): Lokoja Y (7): Sokoto North	32.7	3,051,998.91
4	4067757	Y (3): Asaba Y (4): Lokoja Y (5): Gombe Y (7): Sokoto North	48.03	4,482,798.40
5	3995052	Y (1): Onitsha North Y (3): Asaba Y (4): Lokoja Y (5): Gombe Y (7): Sokoto North	52.8	4,927,998.24

3.5 Conclusions

This chapter finds optimal sites of location allocation facility siting and the demand areas they supply for increasing number of biomass baseload power plants. Optimization outcomes identify optimal sites for efficient operations of renewable baseload generation thereby improving accessibility to electricity and reducing losses; something Nigeria cannot shy away from while tackling the menace of power outages. In descending order of importance, mentioning first the optimal site for a single siting decision scenario to multi siting of up to five plants, the optimal locations are: Asaba, Sokoto North, Lokoja, Gombe, and Onitsha North.

The dire need for baseload power generation necessitates planning for multi-site planning. Our results show that pursuit of biomass development can bring about over 52.8 MW renewable electricity from biomass in the energy mix. It is worthy of note that generation level of 52.8 MW is more than ten times greater than the 0.005 GW (equivalent to 5MW) target generation from biomass by 2050 in the Trajectory 1 of the Nigeria Energy Calculator (NECAL 2050) of the Energy Commission of Nigeria. The three other trajectories in NECAL 2050 namely Trajectory 2, Trajectory 3 and Trajectory 4 in NECAL 2050 have set targets of 1 GW, 4 GW, and 10 GW electricity respectively from biomass towards renewable energy development.

Thus, decision makers have tools available at their disposal when making multi-site decisions for biomass renewable power plants are in Nigeria. Deployment of such tools are integral aspects in the effective working and delivery of agencies and institutions that are stakeholders in renewable energy development. Institutional alignment in the Federal Ministry of Agriculture and Rural Development (FMARD) is one of the organizing themes of Nigeria's APP.

CHAPTER 4: RENEWABLE ENERGY DEVELOPMENT AND POLICY TREND

4.1 Effective Renewable Energy Policy Development in Africa

Africa has 13 percent of global population, but 48 percent of the share of the world's population is without access to electricity (Castellano, 2015). A rule of thumb is that at least one Gigawatt (that is, 1000 megawatts) of electricity generation is needed to meet the demand of one million head of the population in a developed industrial nation (Adeleye, 2016). By extension, that implies that there will be 1000 kWh per capita electricity consumption. Nigeria's per capita consumption is in the range of 124 – 144 kWh (The World Bank, 2018c; Federal Government of Nigeria, 2014). By analyzing mean electricity consumption per capita over the most recent three years of available data, it appears that some African countries do perform above this threshold.

The list in increasing order includes: Gabon, Algeria, Tunisia, Namibia, Egypt, Botswana, Mauritius, Libya, and South Africa with mean electricity consumption per capita at 1,079 kWh, 1,287 kWh, 1,422 kWh, 1,609 kWh, 1,658 kWh, 1,841 kWh, 2,135 kWh, 2,166 kWh, and 4,277 kWh respectively. South Africa stands out and it has the potential to serve as a role model for other African countries. South Africa's National Development Plan (NDP) recognized the need for investment in a strong network of economic infrastructure among which energy infrastructure is a critical component (International Renewable Energy Agency, 2016).

The inadequacy in electricity supply in South Africa was responsible for the introduction of the "Integrated Resource Plan" (IRP) in 2010 (Mdone, 2015). By developing an energy mix over a 20-year planning horizon to meet electricity needs, IRP aims at reducing the consumption of coal as the major energy source from 90% to 42%. The plan also targets an increase in renewables to represent 15% of the total power generation mix in South Africa by the year 2030. Several challenges, such as financial institutions' being unwilling to fund smaller projects, had frustrated the practical implementation of the IRP.

Nevertheless, the Renewable Energy Independent Power Project Procurement Program (REIPPPP) came on board as a public-private partnership program. Relying on private sector actors for realization of planned renewable energy projects, REIPPPP serves as an efficient and innovative approach to South Africa's renewable energy policy. Through its Independent Power Producer Program (IPPP) which has received commendation from the International Renewable Energy Agency (IRENA), South Africa's REIPPPP employs an international bidding process called renewable energy auctions. While grid connections and integration have been a major challenge to REIPPPP, records show that between 2011 and 2016, over 6,327 MW from 102 renewable energy projects were awarded with only two projects being biomass-fired.

4.2 Policy Trend in Nigeria

The Nigerian Electricity Regulatory Commission (NERC), an independent Regulatory Agency established by Electric Power Sector Reform (EPSR) Act 2005, regulates construction, operation, maintenance, and ownership of mini grids. Policy outcome expectations include: upgrade in quality of electricity supply, and rapid expansion of generation capacity. In March 2005, the Electric Power Sector Reform (EPSR) Act was signed into law, allowing private companies to participate as stakeholders in Nigeria's power sector through electricity generation, transmission, and distribution.

Restructuring the power sector through alterations in the energy mix with the goal of achieving energy security, cost management, and environmental stewardship is an integral part of Nigeria's national energy policy (NEP). Specifically, six generating companies (GenCos), and a transmission company (TCN), and eleven electricity distribution companies (DisCos) emerged from the unbundling of the Power Holding Company of Nigeria (PHCN) by the Federal government of Nigeria. NERC grants permit to developers of mini grids to provide, maintain, or construct mini grids in locations termed as "Unserved Areas".

This research attempts to capture such "unserved areas" through the electricity supply deficit in each of the demand areas of the study (Makwe, 2012). Deployment of biomass baseload electricity generation offers itself as a renewable energy option as a strategy for emissions reduction, and sustainability enhancements (Utility Dive, 2018; Matek and Gawell, 2015). According to the ERGP, environmental sustainability is a public policy goal currently at the forefront of Federal Government of Nigeria policy decision making. Therefore, building baseload renewable power plants, such as biomass, in many circumstances produce smaller net emissions (see Appendix 10) than coupling of intermittent sources such as wind or photovoltaic (PV) with either energy storage or gas turbines using fossil fuels (Matek and Gawell, 2015).

4.3 Biomass Power as a Circular Economy Accelerator in Nigeria

Drawing lessons from the experiences of other governments and regions having operational biomass-fired power plants as renewable sources of energy can help ease a gradual yet lasting transition in the belief systems of stakeholders of Nigeria’s power grid diversification and modernization. Knowledge advancement through such learning processes can result in effective policy changes through shifts in perspectives thereby creating an enabling environment for the desired outcome which is improvement in electricity supply in a manner that least impacts the environment. Circular economy depicts this scenario through extraction and utilization of maize residues (as feedstock for electricity generation) which otherwise would have been burnt as wastes.

Circular economy in biomass power development refers to an industrial system that is regenerative or restorative by intention and design. The concept of circular economy presents an opportunity for improvements in current solid waste management through waste valorization and recycling as part of waste-to-energy for boosting a develop economy like Nigeria (Ferronato et al., 2019; World Economic Forum 2018).

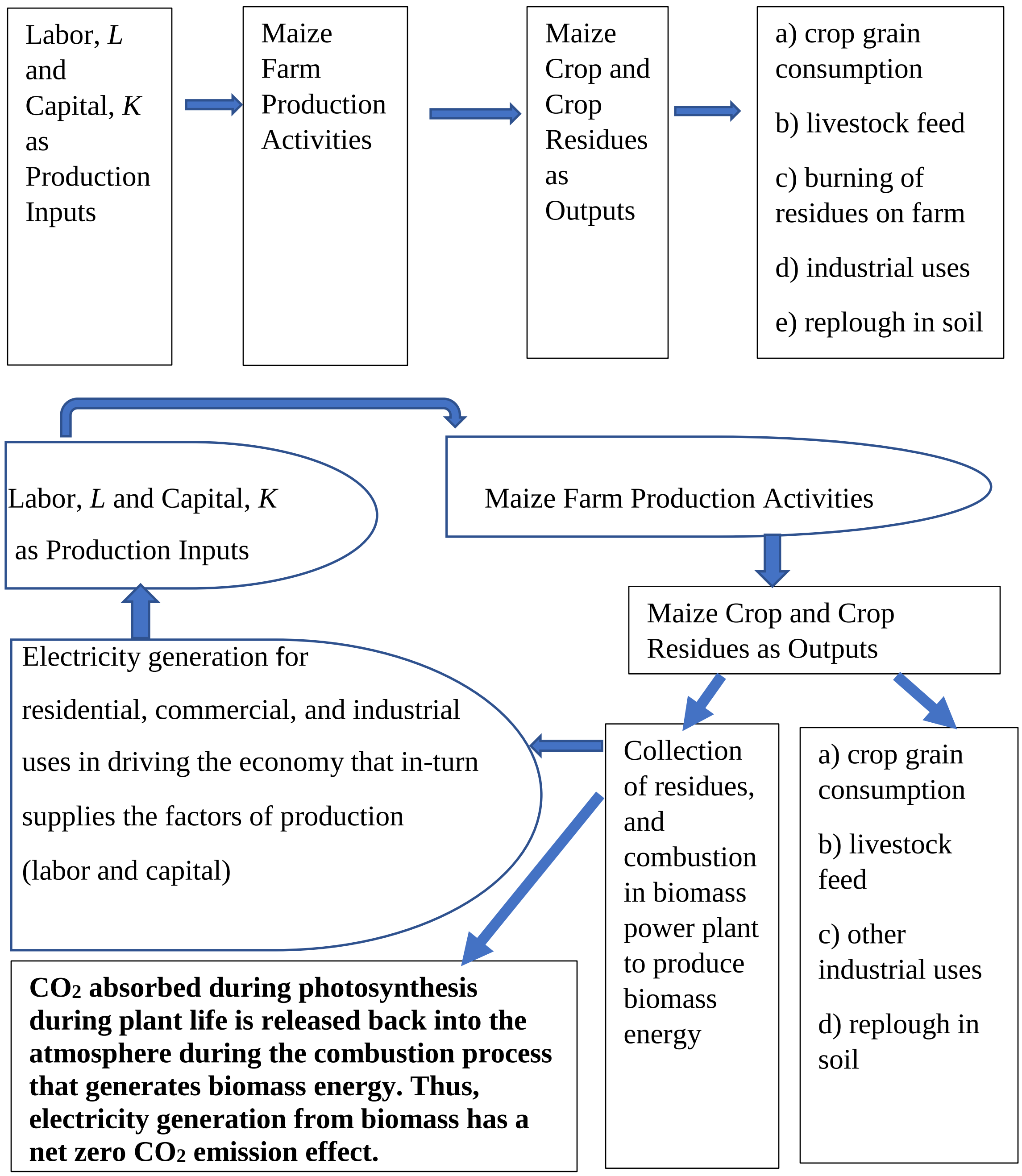

Figure 4.1: Linear versus Circular Economy

The concept of circular economy swaps the end-of-life concept with restoration, pushing for a shift towards the utilization of renewable energy resources, removes the usage of toxic chemicals, which impair return and reuse to the biosphere, and aims for the eradication of waste through the superior design of systems, materials, products, and business models. Figure 4.1 is a diagrammatic representation of linear and circular economy. As an alternative to traditional linear economy, a circular economy pushes for a shift to renewable energy and materials, deploys biomass power generation technology, seeks to extract the maximum value from crop output, replough recovered biological resources to the environment, then regenerate and recover materials (such as maize husk) and products (such as biomass energy) at the end of each service life.

Such products as biomass energy are integral to the provision of services like electricity generation and supply with economy-wide effects. Benefits of a circular economy include potential economic growth through improvements the balance of trade and GDP of Nigeria, additional job creation, generate a new wave of innovation that births new business services across the economy, improvement in resource efficiency thereby increasing competitiveness, increase in household disposable income, reduction in demand for primary materials thereby mitigating demand-driven price volatility on raw material markets (for example, demand for iron ore) while simultaneously enhancing security supply of raw materials, and reducing pressures on the environment (Trifonova, 2017; Bourguignon, 2016).

Therefore, a circular economy will not only reduce crop residue waste and environmental impacts of haphazard burning associated with a linear economy but will contribute to an improvement in resource productivity which is the focus of Nigeria's Agricultural Promotion Policy. NIRP identifies agriculture and manufacturing as driver sectors. Therefore, policies that impact the biological cycle of maize cultivation towards better productivity will have a moderating effect on the techno-economic processes of the manufacturing and industrial sectors that utilize the erstwhile residue wastes. Examples of such policies can include a farm input price subsidy, agricultural waste collection framework, and environmental regulations that dis-incentivizes the haphazard handling of crop residues.

In addition, technical and cost efficiency of the commercial, industrial and manufacturing centers in the value-chain shown in Figure 4.1 such as energy and materials laboratories, feedstock preparation, extraction, and combustion components will have moderating effect towards achieving NEP objective of appropriate cost in electricity delivery in a manner that is environmentally friendly (ECN, 2013). Does that imply that circular economy will be without challenges? Not at all. The reason is, financial investments required for a circular economy are high. For example, acquisition of new technologies and collaborative networks requires substantial funding in transitioning from a linear to a circular economy (Tom et al., 2018; Vasileios et al., 2015; Trifonova, 2017).

Externalities such as absence of patents and ineffective pollution taxes can also disincentivize players in the circular value chain in Figure 4.1 to fully participate in the circular economy (Tom et al., 2018; Trifonova, 2017). In addition, high unforeseen contracting costs, and regulatory failures such as incoherence between policy instruments, ineffective or insufficient policies, creation of administrative burden, poor implementation of policies, and lack of harmonized standards constitute barriers to the working of the circular economy. Overcoming these challenges is critical for salvaging the estimated 15.6% sales value (equivalent to $12.6 billion dollars based on 2013 retail sales value) that Nigerian small and medium enterprises (SMEs) which are potential players in the global circular economy value chain lose to power outages (Rizos et al., 2016; The World Bank, 2014; National Bureau of Statistics, 2013).

CHAPTER 5: ECONOMIC AND POLICY IMPLICATIONS OF BIOMASS UTILIZATION FOR NIGERIA

5.1 Significance of Biomass as Reliable Baseload Electricity for Nigeria

Baseload power is a key element in meeting electricity demand effectively. The reason is, an electricity grid cannot function without substantial baseload power, that is, the minimum level of power on the system. Biomass-fired plants can achieve such baseload electricity generation threshold through combustion of crop residues to produce high temperature steam that drive turbines in generating electricity, with the potential for improvement in energy security through less dependence on fossils (Alidrisi and Demirbas, 2016), reduction in GHG emissions with zero net greenhouse effect (Mohd Idris et al., 2018; Matek and Gawell, 2015), improvement in sustainability linked with power and heat generation, and promoting economic development in Nigeria through potential revenue generation from residue feedstock, job creation, and reduction of lost sales values due to power outages (Ruiz et al., 2018; Matek and Gawell, 2015).

Biomass is promising as a flexible, cost efficient by ensuring a minimum cost grid, able to ramp, and reliable source of power for baseload renewable electricity generation without intermittency, and possibility for integration without any additional backup (Matek and Gawell, 2015). Acting flexibly implies that biomass is a renewable baseload source capable of adjusting to the electrical grid's needs with potential advantages not yet acknowledged in the regulatory system. One of the objectives of Nigeria Energy Policy (NEP) is to ensure the development of Nigeria's energy resources, with diverse energy resource option towards achieving national energy security and an efficient delivery system (ECN, 2013).

Thus, biomass baseload power generation can contribute to power grid modernization as an effective technology option in overcoming the challenge of shortages in power generation in Nigeria. Being a baseload power source, biomass could displace fossil fuels without higher costs. An appropriate cost will be a cost value that is at least lower than back-up diesel generators cost of energy (COE) which is about US $1.075/kWh. Consequently, biomass baseload development in Nigeria contributes to achieving another goal of NEP which is to guarantee adequate, steady and sustainable supply of electricity to the various sectors of the economy at appropriate cost and in a manner that is environmentally friendly. Such generation has potential to offset current self-generation through petrol and diesel generators which is nearly over 6,000 MW (The World Bank, 2018c).

5.2 Economic and Policy Implications of Biomass Baseload Development in Nigeria

Economic performance is increasingly linked to global competitiveness, thereby necessitating building energy infrastructure required for achieving growth targets in accordance with global standards (National Planning Commission, 2015). The steady supply of electric power is a main constraint to productivity of industrial activities in Nigeria. Electricity generation improvements is foundational to solving Nigeria's power outage nightmare. Such developments will enhance competitiveness of the entire commercial and industrial sectors in Nigeria thereby enabling the unleashing of productivity across the board through a removal or reduction of structural impediments to Nigeria's industrialization.

Nigerian integrated infrastructure master plan (NIIMP) considers electric power generation and transmission capacity expansion as an issue of priority for national development. Environmental policies that disincentive haphazard burning of crop residues coupled with an organized residue collection framework is strategic to development of biomass power in Nigeria. Public-private partnerships (PPP) will ensure fresh investments in biomass renewable energy infrastructural development in Nigeria as the results of this research suggests. Financing mode options to overcome financial challenges include: build-operate-transfer (BOT), transfer-operate-transfer (TOT), government investments, or public-private partnership (PPP) as is currently the case in the signed MoU in the planned biomass in Kogi state (Xin-gang et al., 2016).

PPP endears combination of financial funds and social funds, alleviation of the pressure on financial sector, reduction of the construction period and improvements in the operational efficiency (Xin-gang et al., 2016). Consequently, cost efficiency is achieved through improvements in supervisions, service quality and operational efficiency. Such new spending on infrastructure will compensate for historical low value spending on infrastructure by both public and private sectors, thereby alleviating the current level of gross insufficiency in grid supply of electricity. The resultant effect will be productivity improvement of core driver sectors with positive multiplier effect economy-wide. Policy makers can advocate, take actions to change laws, evaluate policies, modify set of regulations and guidelines, quantify performance indicators, provide impetus for better policy implementations, and facilitate public private partnerships (PPP) on issues of competitiveness and productivity in key sectors like power, industry, and agriculture.

It is important to note, however, that the wet season agricultural performance survey (WSAPS) is missing in the data on dry season agricultural production which is a very important of agricultural practice in Nigeria. Dry season agriculture, commonly referred to as “Fadama” enjoys wide support from multilateral agencies like the World Bank to boost food production in Nigeria. Specifically, the Agricultural Transformation Agenda (ATA) program is often implemented in the dry seasons for certain crops. By implication, such well-funded programs may have crop production levels that could alter the optimal solution of analyses in this research.

Another limitation of the study includes errors of distance measurements that might have affected the minimization objective value. Inability to obtain detailed information about farm level input and cost operations, their geographical coordinates and their proximity to major infrastructural and protected environmental sites limits the inclusion of more weighing criteria in our relativity suitability and location-allocation modelling. Reliable data on such factors are vital for power plant siting toward narrowing the electricity supply deficit which stakeholders' currently estimate to be about 135,000 – 155,000 MW, based on installed capacity.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

Relative suitability analysis and location-allocation optimization in this research constitute model application presenting a platform for policy learning for siting renewable power generation infrastructure. The relationship between electricity supply and sales value salvaged is a critical import of this research. Such relationship might be more location specific with varying magnitude across space in the Nigerian economy. For instance, urban areas having high density commercial and industrial activity may have higher magnitude of salvaged sales value per MW electricity supplied compared with rural areas.

This research identified Anambra as the best suitable site for maize residue biomass-fired power generation siting based on cost productivity and crop output productivity indexes. Such move will be a major energy and economic infrastructural development in the state as Anambra state currently has no operation baseload power plant. Multiple siting decisions based on weighted minimized cost of transporting available energy (which serves as a proxy for electricity transmission and accessibility) solved optimal distance and electricity supply deficit in megawatts miles (MW miles). Each scenario with increasing numbers of power plants presents potential for energy production and electricity generation.

This research has employed visualization and optimization tools such as GIS and LINGO to map spatial distribution of crop productivity variables to perform mixed integer linear programming in contributing to facility siting decision making for renewable baseload electricity generation. As NERC's feed-in-tariff for biomass power plants stands at 1 - 10MW capacity, any significant improvement in electricity generation from biomass will require an inundation of the Nigerian power sector landscape with biomass power plants. Considering the current generation shortage in Nigeria, many independent power producers (IPPs) will be necessary.

Therefore, policies that create conducive atmosphere for IPPs is essential. Location-allocation modelling with considerations from transmission are promising for multi-siting decisions that simultaneously allocate power generation to demand areas. Thus, findings from such analyses propose actionable pathways for effective baseload sustainable biomass-fired power generation siting plans, thereby enhancing policy formulations and decision making. Nevertheless, NAERLS should partner with NBS at a higher level of synergy in data collection thereby resulting in better data quality. Too many gaps from year to year and over various agro-ecological zones limit data analysis.

ADPs approached initially complained of insufficient funding as responsible for lack of data. Thus, government at all levels should collaborate with multi-lateral organizations in making funds available to ADPs. Since the WSAPS includes interviews in selected communities, the team of survey personnel should be equipped with equipment such as portable hand-held global position system (GPS) units to record the geographical coordinates of farm locations in the survey area. Having geographical coordinates of the farm operations where biomass residues are available will afford an opportunity for detailed research on the distribution and spatial layout of feedstock in a finer detail.

In other words, specific potential location of a power plant can be determined from spatial analysis. Thus, having data at finer levels such as maize farms and the coordinates of such locations in the biomass value chain is vital for more accurate optimization analyses. Such analyses will have significant implications towards sustainable land use management and productivity for biomass energy and Nigeria's agro-ecological economy. The reason is, over time utility companies having biomass power plants will have to procure residue feedstock from an array of farm locations that serves as potential suppliers with each of those farms having restrictions on capacity.

Detailed consistent data reporting in WSAPS will allow for inclusion of farm inputs and production resources in econometric analyses that can inform policy-making as it relates to improved productivity in maize production. Core implication of the research approach through productivity index is the opportunity for active government regulatory operations in enhancing energy infrastructure permitting, thereby increasing the share of renewable energy in Nigeria's energy mix. Such developments will provide opportunity for crop residue fired renewable energy economics, with implications for agricultural economics on productivity centered feedstock production which is an integral part of a circular economy in overcoming the fundamental infrastructural issue of power outages hindering productive activities in Nigeria.

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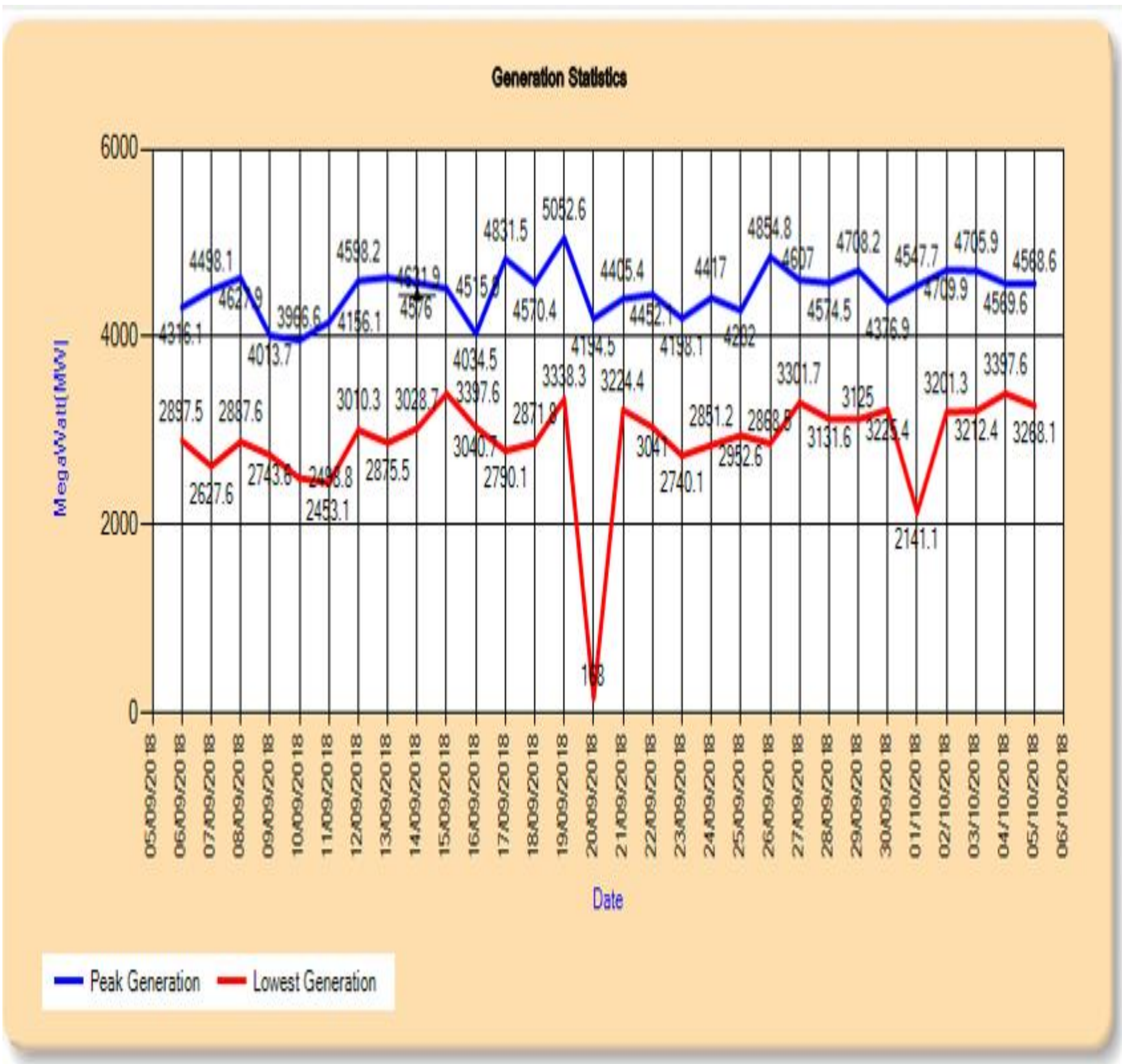
APPENDIX 1: Nigerian Electricity System Operator Statistics



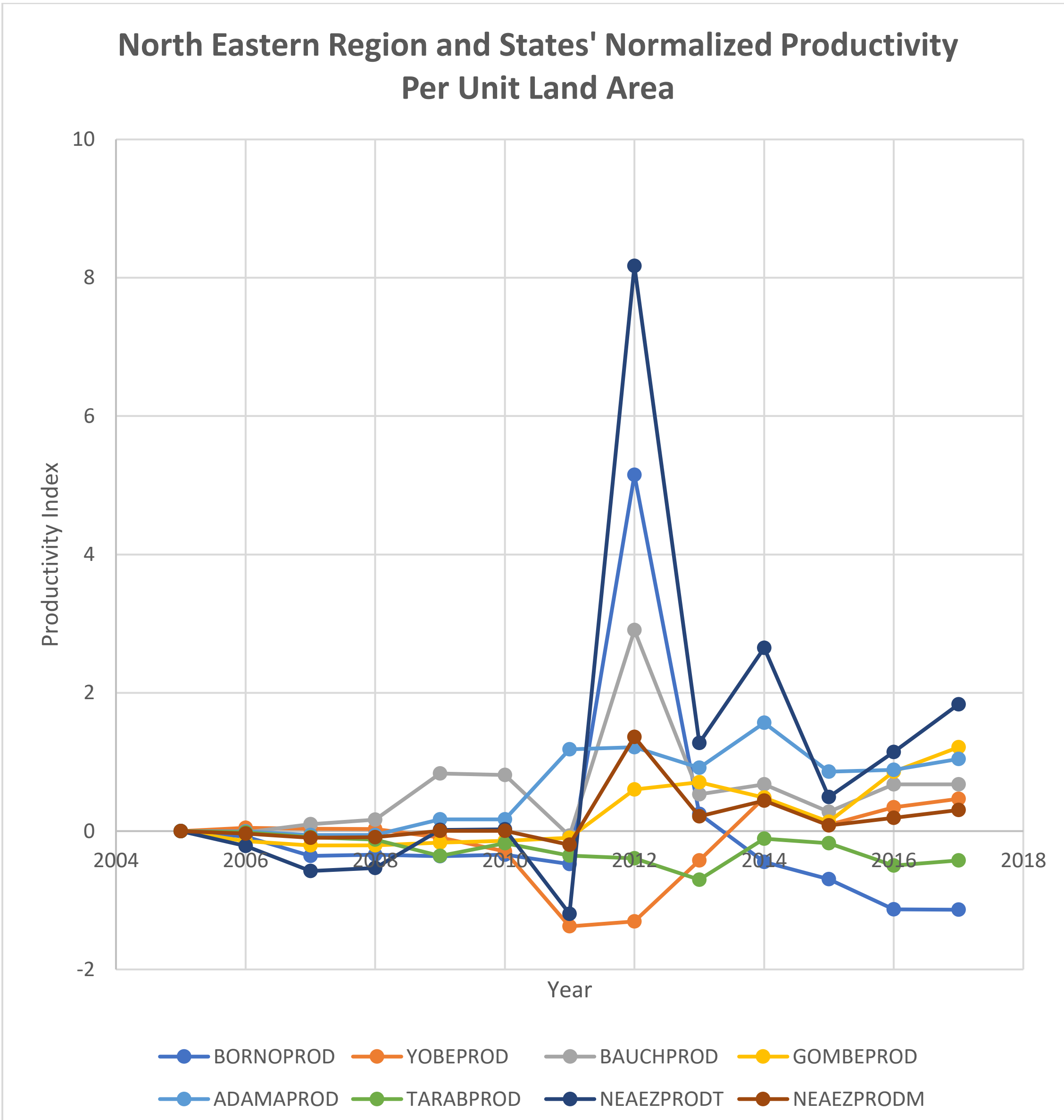
2018 Maximum Nigerian Electricity Generation Output Attained by All Generation Units/Companies at Any Given Point Within the Day (Measured in Megawatt) **Source:** NESO

APPENDIX 2: Summary Statistics of Factors in Maize Crop and Residue Production

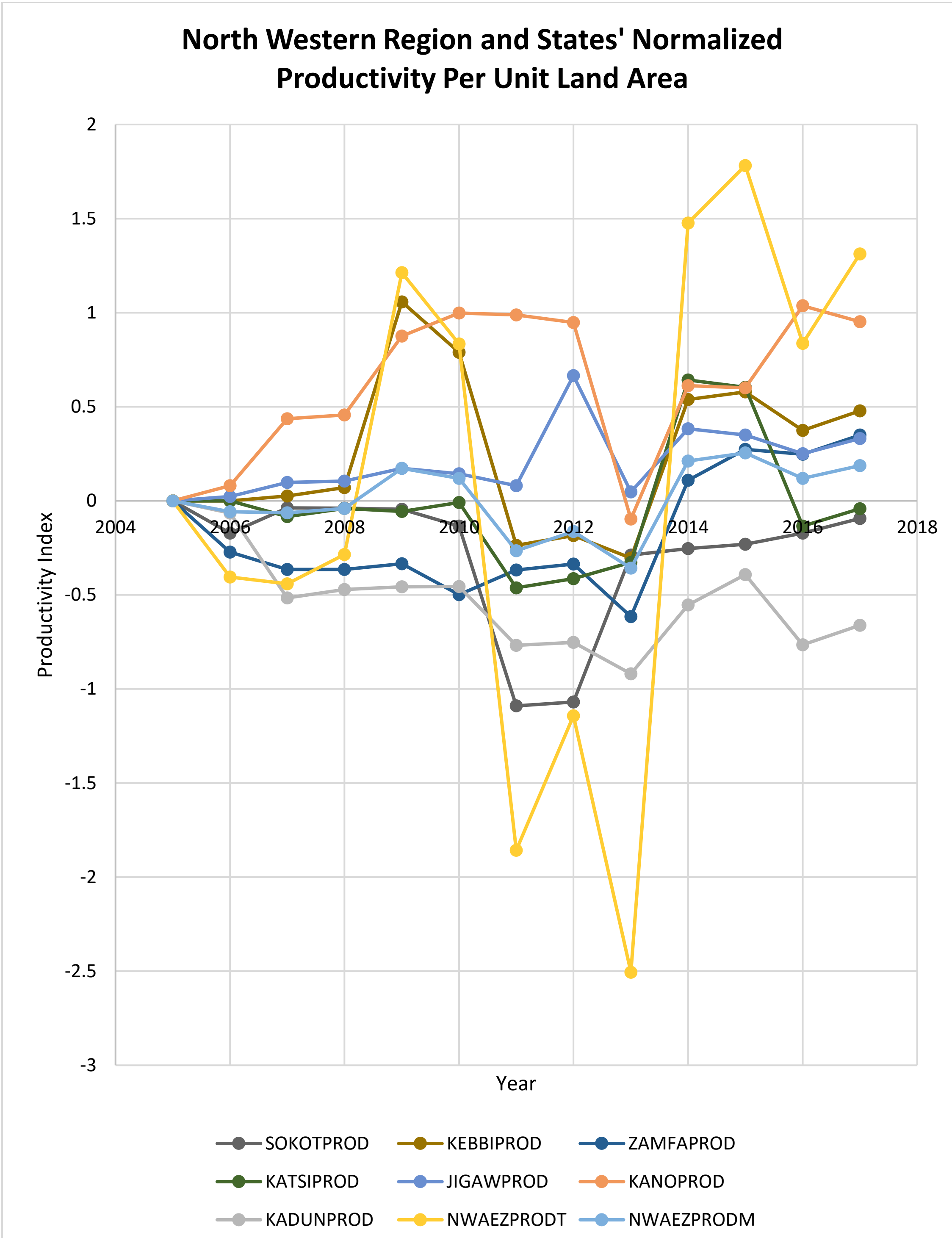
Statistic	***Mland***	***Mharvest***	***MResidue***	***Mprodul***	***MCostProd***	***MCCPRI***
Mean	154.922	3102.772	596.687	1.748	184.097	111.324
Standard Error	14.659	364.351	70.067	0.060	19.139	14.791
Median	150.8	2457.828	472.659	1.736	166	83.36
Mode	N/A	N/A	N/A	1.888	165	N/A
Standard Deviation	89.165	2216.259	426.204	0.364	116.420	89.972
Sample Variance	7950.323	4911802.741	181649.4	0.133	13553.67	8095.018
Kurtosis	3.724	3.575	3.575	0.165	7.056	16.388
Skewness	1.563	1.617	1.617	0.211	2.300	3.578
Range	430.8	10578.499	2034.326	1.741	607.5	524.47
Minimum	43.35	555.811	106.887	0.953	45	29.62
Maximum	474.15	11134.31	2141.213	2.694	652.5	554.09
Sum	5732.1	114802.549	22077.41	64.692	6811.6	4118.985
Count	37	37	37	37	37	37

Terms	**VARIABLE DESCRIPTION**	**MEASUREMENT UNIT**
Mland	Mean Estimate of Land Area for Cultivation	Thousand Hectares
Mharvest	Mean Harvest	Thousand Tons
MResidue	Mean Residue	Tons
Mprodul	Mean Crop Productivity Per Unit Land	Tons per unit hectare
MCostProd	Mean Production Cost Per Unit Land Area	Thousand Naira per hectare
MCCPRI	Mean Combined Cost Productivity Ratio Index	Thousand naira per ton

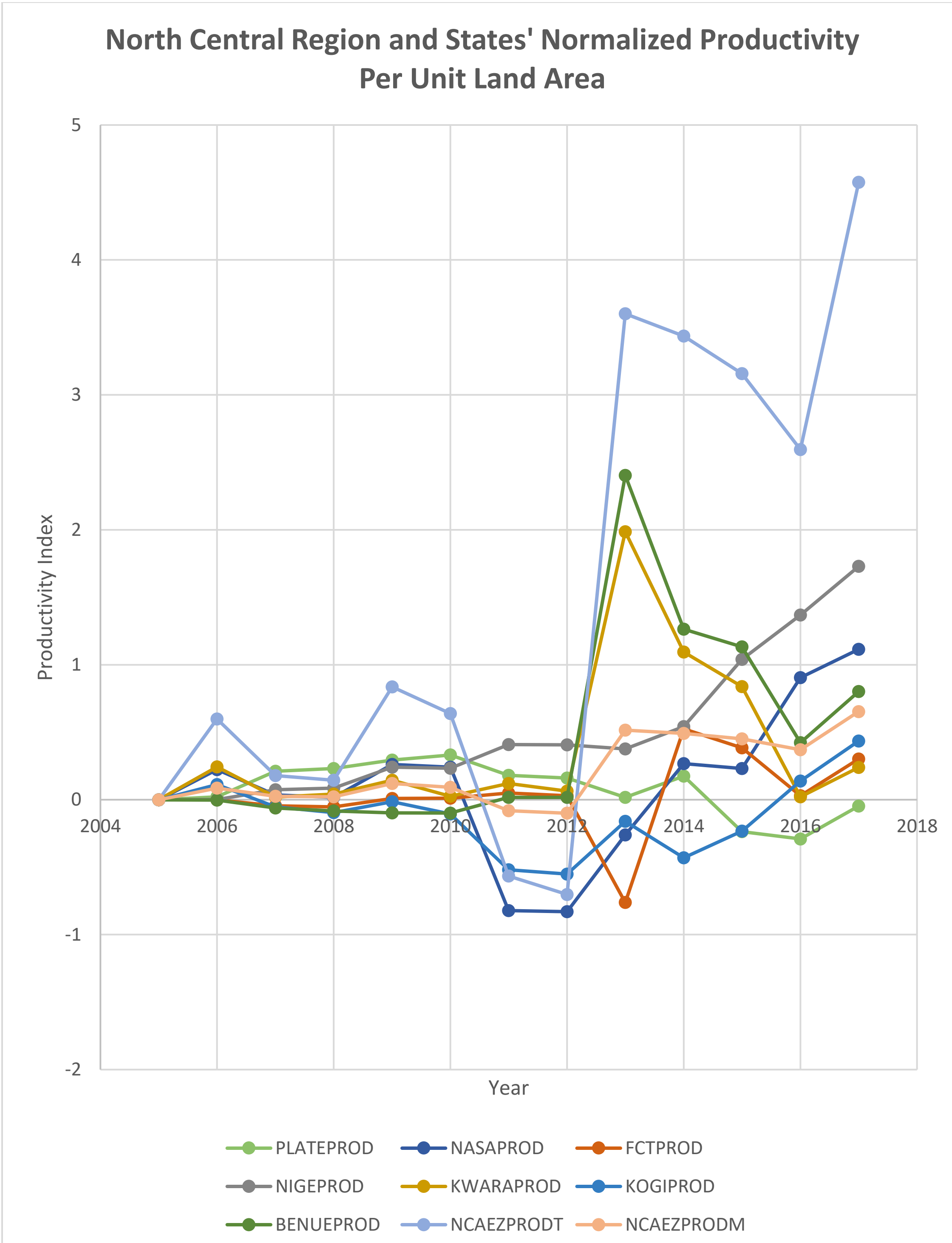
APPENDIX 3: Trend of Productivity Index in Maize Production Across Agro-Ecological Zones



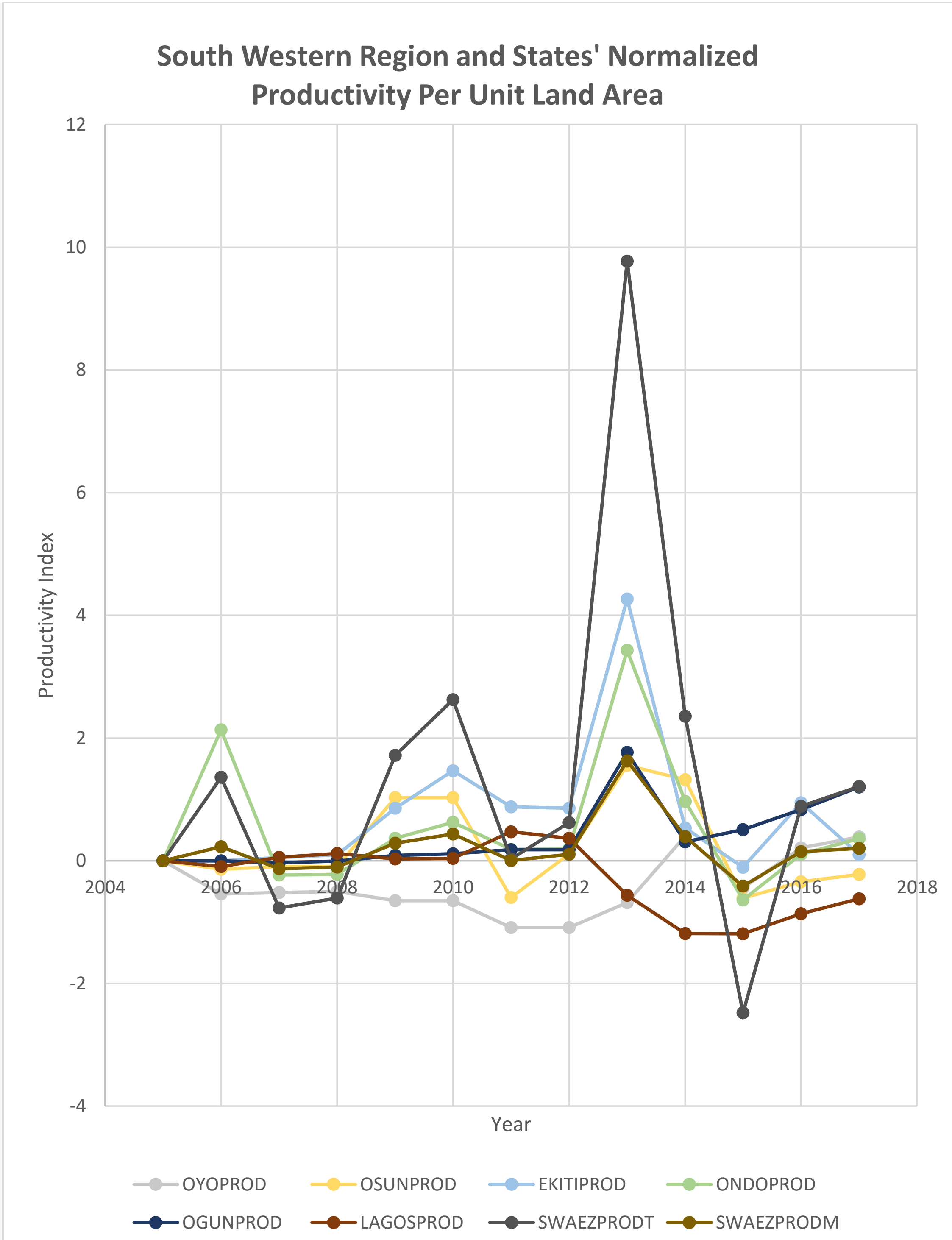
Graph of Normalized Productivity Per Unit Land in North Western Agro-Ecological Zone



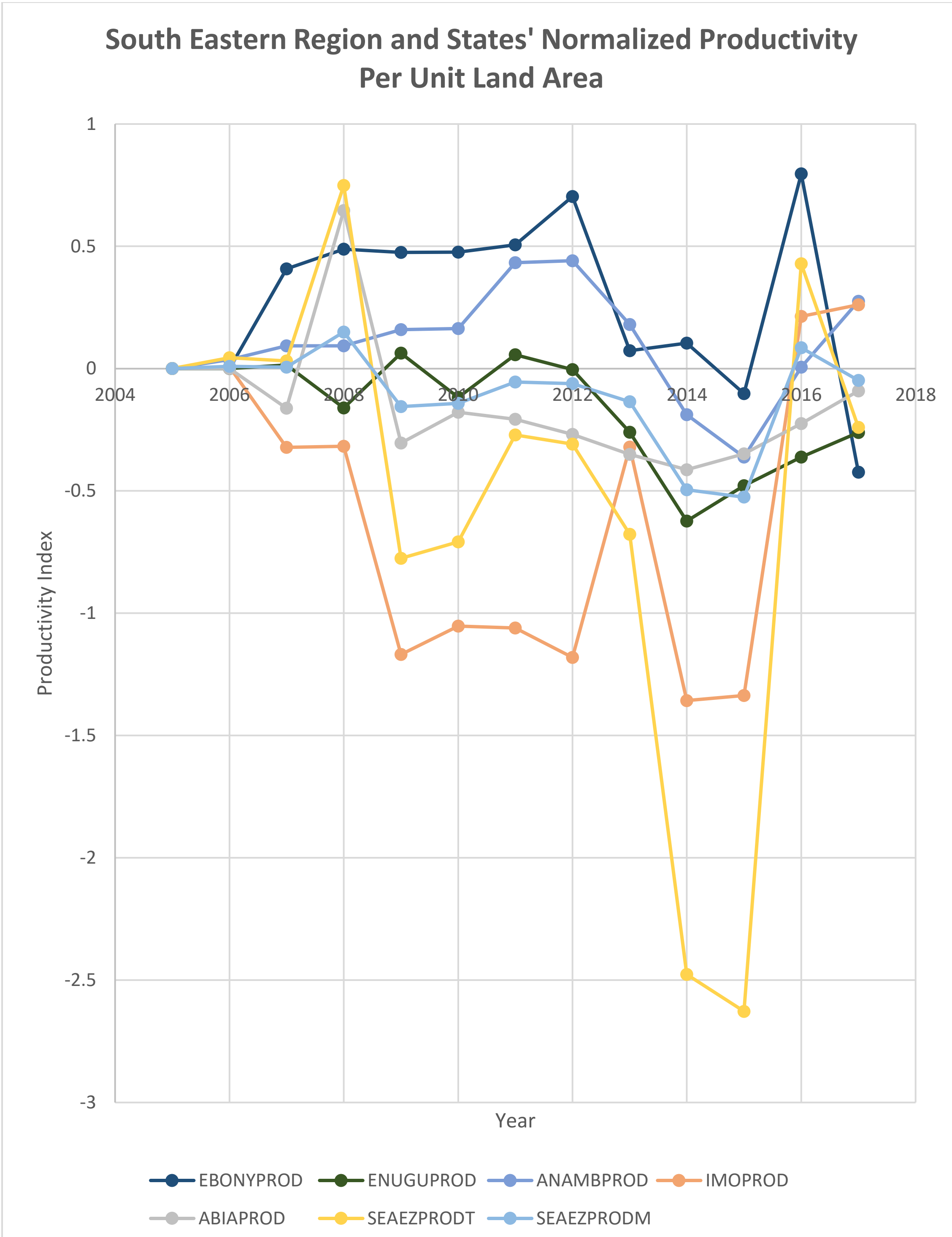
Graph of Normalized Productivity Per Unit Land in North Western Agro-Ecological Zone



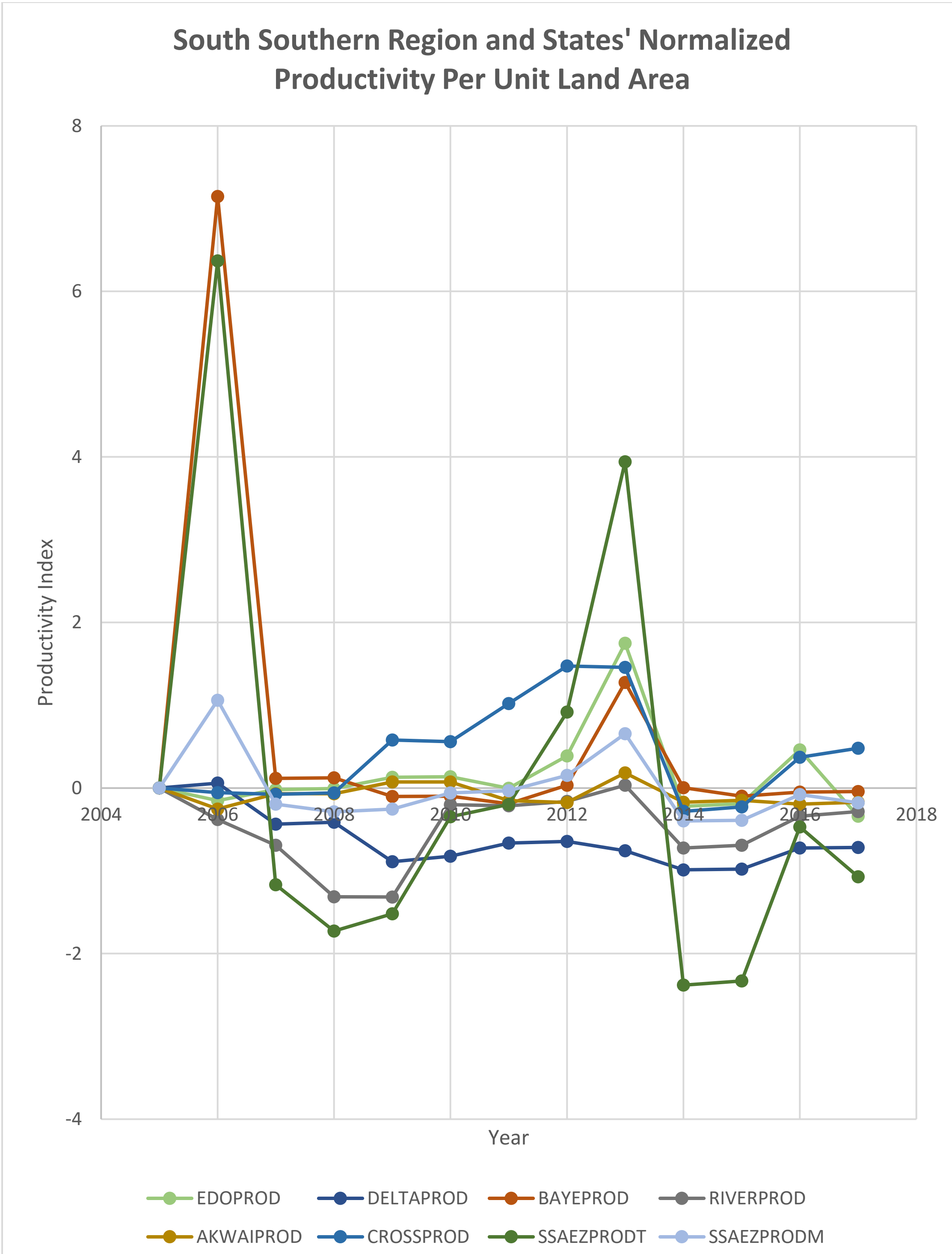
Graph of Normalized Productivity Per Unit Land in North Central Agro-Ecological Zone



Graph of Normalized Productivity per Unit Land in South Western Agro-Ecological Zone



<u>Graph of Normalized Productivity per Unit Land in South Eastern Agro-Ecological Zone</u>



Graph of Normalized Productivity per Unit Land in South Southern Agro-Ecological Zone

APPENDIX 4: Electricity Distribution Area Supply Information

Owner	Coverage State Area	Electricity Distribution Area Supply Deficit (MW)	State Per Capita Supply Deficit (MW/per ten thousand persons)	State Supply Deficit (MW)
Kann Consurtium Utility Company Plc	Abuja	500.25	0.031	110.484
Kann Consurtium Utility Company Plc	Niger	500.25	0.031	172.236
Kann Consurtium Utility Company Plc	Kogi	500.25	0.031	138.694
Kann Consurtium Utility Company Plc	Nasarawa	500.25	0.031	78.213
Vigeo Power Consurtium	Edo	690.32	0.039	165.204
Vigeo Power Consurtium	Delta	690.32	0.039	220.857
Vigeo Power Consurtium	Ondo	690.32	0.039	182.208
Vigeo Power Consurtium	Ekiti	690.32	0.039	127.569
West Power and Gas and NEDC/KEPCO	Lagos	1087	0.087	1091.937
Interstate Electric Limited	Enugu	441.72	0.02	88.22
Interstate Electric Limited	Abia	441.72	0.02	74.54
Interstate Electric Limited	Imo	441.72	0.02	108.18
Interstate Electric Limited	Anambra	441.72	0.02	110.56
Interstate Electric Limited	Ebonyi	441.72	0.02	57.6
Integrated Energy Distribution and Marketing Company	Oyo	385.24	0.018	141.138
Integrated Energy Distribution and Marketing Company	Ogun	385.24	0.018	93.924
Integrated Energy Distribution and Marketing Company	Osun	385.24	0.018	84.708

Integrated Energy Distribution and Marketing Company	Kwara	385.24	0.018	57.474
Aura Energy Limited	Plateau	212.16	0.011	46.2
Aura Energy Limited	Bauchi	212.16	0.011	71.907
Aura Energy Limited	Benue	212.16	0.011	63.162
Aura Energy Limited	Gombe	212.16	0.011	35.827
Sahelon Power SPV Limited	Kebbi	255.12	0.01	44.4
Sahelon Power SPV Limited	Zamfara	255.12	0.01	45.15
Sahelon Power SPV Limited	Kaduna	255.12	0.01	82.52
Sahelon Power SPV Limited	Sokoto	255.12	0.01	78.31
Sahelon Power SPV Limited	Kano	377	0.014	183.078
Sahelon Power SPV Limited	Jigawa	377	0.014	81.592
Sahelon Power SPV Limited	Katsina	377	0.014	109.634
4 Power Consurtium	Rivers	369.62	0.02	146.08
4 Power Consurtium	Cross River	369.62	0.02	77.32
4 Power Consurtium	Bayelsa	369.62	0.02	45.56
4 Power Consurtium	Akwa-Ibom	369.62	0.02	109.64
Integrated Energy Distribution and Marketing Company	Adamawa	68.36	0.004	16.992
Integrated Energy Distribution and Marketing Company	Borno	68.36	0.004	23.44
Integrated Energy Distribution and Marketing Company	Taraba	68.36	0.004	12.268
Integrated Energy Distribution and Marketing Company	Yobe	68.36	0.004	13.176

Source: Shonibare (2014)

Electricity Peak Load Supply Deficit across Demand Area States in Nigeria

Demand State Area	**State Supply Deficit Per Thousand Persons (MW)**	**LGA Potential Site**
Anambra	110.56	Onitsha North
		Onitsha South
Kogi	138.694	Lokoja
Gombe	35.827	Gombe
Sokoto	78.31	Sokoto North
Yobe	13.176	Damaturu
Delta	220.857	Asaba

Source: Shonibare (2014)

APPENDIX 5: Annual Crop Output Productivity Index of States in Maize Cultivation (measured in tons per unit hectare)

STATE						
YEAR	**BORNO**	**YOBE**	**BAUCHI**	**GOMBE**	**ADAMAWA**	**TARABA**
2005	1.486	1.560	1.518	1.500	1.129	1.775
2006	1.405	1.608	1.500	1.357	1.126	1.757
2007	1.128	1.593	1.619	1.292	1.074	1.686
2008	1.144	1.590	1.682	1.294	1.074	1.654
2009	1.123	1.468	2.349	1.334	1.297	1.415
2010	1.144	1.265	2.329	1.359	1.297	1.599
2011	1.010	0.183	1.450	1.403	2.310	1.419
2012	6.638	0.253	4.423	2.101	2.342	1.384
2013	1.735	1.134	2.049	2.204	2.046	1.073
2014	1.040	2.043	2.192	1.984	2.694	1.666
2015	0.792	1.650	1.798	1.635	1.988	1.600
2016	0.357	1.906	2.195	2.361	2.016	1.276
2017	0.350	2.026	2.192	2.712	2.170	1.352

Source: National Agricultural Extension and Research Liaison Services (2017)

STATE							
YEAR	**SOKOTO**	**KEBBI**	**ZAMFARA**	**KATSINA**	**JIGAWA**	**KANO**	**KADUNA**
2005	1.232	1.143	1.505	1.410	1.311	1.604	2.711
2006	1.060	1.143	1.233	1.410	1.333	1.684	2.646
2007	1.194	1.169	1.140	1.326	1.408	2.041	2.194
2008	1.193	1.213	1.140	1.369	1.416	2.060	2.239
2009	1.187	2.200	1.171	1.353	1.483	2.480	2.254
2010	1.098	1.933	1.007	1.400	1.455	2.602	2.255
2011	0.142	0.906	1.137	0.948	1.391	2.592	1.942
2012	0.162	0.958	1.169	0.997	1.975	2.552	1.958
2013	0.943	0.839	0.889	1.082	1.357	1.508	1.792
2014	0.978	1.682	1.614	2.052	1.693	2.216	2.157
2015	1.002	1.721	1.778	2.014	1.660	2.205	2.319
2016	1.060	1.517	1.752	1.275	1.562	2.641	1.946
2017	1.139	1.621	1.854	1.367	1.641	2.557	2.049

Source: National Agricultural Extension and Research Liaison Services (2017)

STATE							
YEAR	PLATEAU	NASARAWA	FCT	NIGER	KWARA	KOGI	BENUE
2005	2.303	1.800	1.851	1.180	1.354	1.652	1.438
2006	2.325	2.024	1.851	1.180	1.598	1.765	1.435
2007	2.514	1.836	1.806	1.253	1.372	1.600	1.376
2008	2.534	1.818	1.797	1.265	1.396	1.556	1.355
2009	2.596	2.062	1.860	1.420	1.499	1.638	1.340
2010	2.634	2.042	1.862	1.413	1.379	1.547	1.340
2011	2.484	0.979	1.902	1.588	1.473	1.133	1.455
2012	2.463	0.970	1.880	1.587	1.418	1.102	1.456
2013	2.320	1.539	1.089	1.556	3.340	1.493	3.842
2014	2.479	2.067	2.377	1.721	2.448	1.221	2.702
2015	2.066	2.031	2.235	2.220	2.192	1.420	2.571
2016	2.013	2.705	1.880	2.548	1.376	1.791	1.861
2017	2.256	2.915	2.154	2.909	1.593	2.088	2.240

Source: National Agricultural Extension and Research Liaison Services (2017)

STATE						
YEAR	OYO	OSUN	EKITI	ONDO	OGUN	LAGOS
2005	1.880	1.734	1.296	2.134	1.352	2.470
2006	1.337	1.597	1.296	4.267	1.352	2.375
2007	1.360	1.639	1.347	1.904	1.321	2.525
2008	1.381	1.640	1.392	1.913	1.347	2.587
2009	1.228	2.764	2.152	2.500	1.439	2.501
2010	1.230	2.763	2.763	2.759	1.467	2.509
2011	0.791	1.137	2.177	2.316	1.530	2.944
2012	0.792	1.845	2.151	2.329	1.531	2.837
2013	1.197	3.290	5.562	5.562	3.120	1.905
2014	2.283	3.055	1.832	3.103	1.662	1.285
2015	1.436	1.124	1.190	1.497	1.859	1.280
2016	2.093	1.392	2.239	2.239	2.186	1.605
2017	2.267	1.512	1.397	2.497	2.556	1.849

Source: National Agricultural Extension and Research Liaison Services (2017)

STATE					
YEAR	**EBONYI**	**ENUGU**	**ANAMBRA**	**IMO**	**ABIA**
2005	1.632	1.830	1.923	2.477	1.514
2006	1.632	1.830	1.960	2.484	1.514
2007	2.039	1.845	2.016	2.155	1.351
2008	2.120	1.669	2.017	2.160	2.160
2009	2.107	1.893	2.083	1.308	1.210
2010	2.108	1.713	2.087	1.424	1.336
2011	2.138	1.887	2.356	1.417	1.306
2012	2.335	1.826	2.364	1.296	1.245
2013	1.705	1.570	2.104	2.156	1.163
2014	1.736	1.207	1.735	1.120	1.101
2015	1.530	1.351	1.562	1.140	1.165
2016	2.428	1.469	1.929	2.690	1.289
2017	1.208	1.568	2.198	2.738	1.422

Source: National Agricultural Extension and Research Liaison Services (2017)

STATE						
YEAR	**EDO**	**DELTA**	**BAYELSA**	**RIVERS**	**AKWA-IBOM**	**CROSS-RIVER**
2005	1.549	2.500	1.219	1.720	1.259	1.691
2006	1.400	2.559	8.366	1.339	1.007	1.636
2007	1.531	2.063	1.338	1.029	1.192	1.617
2008	1.546	2.087	1.343	0.408	1.1924	1.633
2009	1.679	1.611	1.119	0.404	1.335	2.272
2010	1.688	1.678	1.120	1.519	1.335	2.252
2011	1.548	1.834	1.030	1.506	1.109	2.712
2012	1.937	1.856	1.254	1.559	1.085	3.165
2013	3.298	1.743	2.495	1.754	1.443	3.147
2014	1.330	1.513	1.223	0.995	1.087	1.409
2015	1.360	1.521	1.120	1.031	1.112	1.462
2016	2.013	1.777	1.172	1.382	1.064	2.063
2017	1.208	1.784	1.179	1.436	1.088	2.171

Source: National Agricultural Extension and Research Liaison Services (2017)

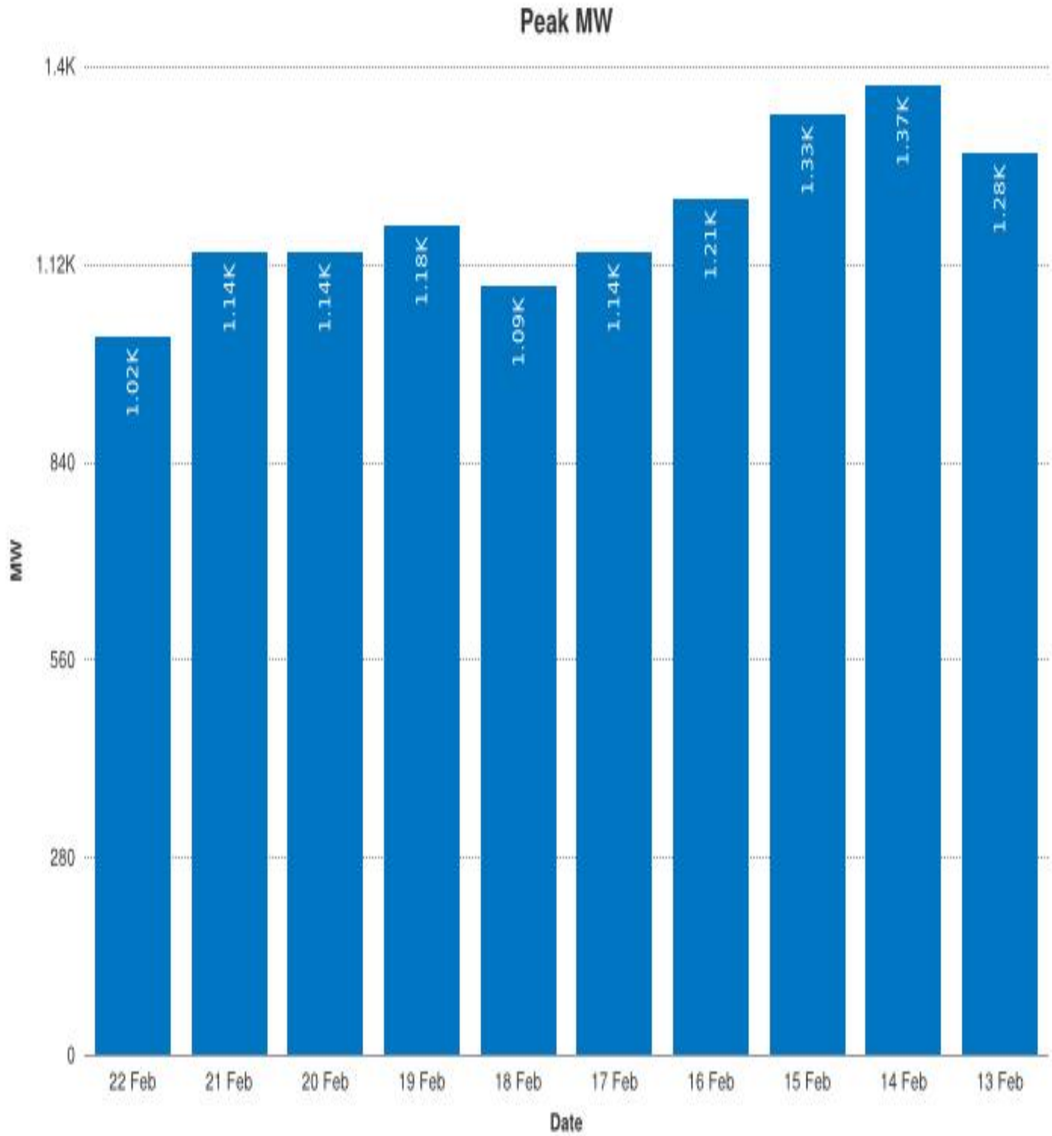
APPENDIX 6: Energy Resources Potential in Nigeria

Resource Type		Reserves		Production	Domestic Utilization (natural units)
		Natural Units	**Energy Units (Btoe)**		
Hydro power	Small Hydro	3500MW	0.34 (over 40 years)	30MW	30MW
	Large Hydro	11,250MW	0.8 (over 40 years)	1938MW	1938MW
Wind		2-4 m/s at 10m height (main land)	0.0003 (4 m/s @ 12% probability, 70m height, 20m rotor, 0.1% land area, 40 years	-	-
Coal and lignite		2.175 billion ton	1.52	-	-
Natural Gas		187 Trillion	4.19	6 billion SCF/day	3.4 billion SCF/day
Tar sands		31 billion barrels of equivalent	4.31	Insignificant	Insignificant
Solar Radiation		3.5 – 7.0 $kWh/m^2/day$ (4.2 million MWh/day using 0.1% land area)	5.2 (40 years and 0.1% land area)	6MWh/day	6MWh/day
Crude oil		36.22 billion barrels	5.03	2.5 million barrels/ day	450,000 barrels/day
Biomass	Fuel Wood	11million hectares of Forest and wood land	-	0.120 million ton/day	0.120 million ton/day

		excess of 1.2 m ton/day			
	Animal Waste	211 million assorted animals	-	0.781 million ton of waste/day	None
	Energy crops and agricultural residue	28.2 million hectares of arable land (=30% of total land)	-	0.256 million ton of assorted crops/day	None

Source: National Bureau of Statistics, Energy Commission of Nigeria (2010)

APPENDIX 7: Constrained Daily Electricity in Nigeria



2018 Nigerian Daily Total Constrained Electric Power **Source: NERC**

APPENDIX 8: Agro-Ecological Variables Mean Values

State	Mprodul	MResidue	MRenegpot	Mharvest	MCostProd	MCCPRI
Borno	1.489	921.985	1843.969	4794.32	226	151.82
Yobe	1.406	234.387	468.773	1218.81	73.5	52.27
Bauchi	2.100	980.233	1960.465	5097.21	165	78.58
Gombe	1.734	664.229	1328.458	3453.99	67.2	38.77
Adamawa	1.736	648.285	1296.569	3371.08	421.9	243.07
Taraba	1.512	1078.054	2156.109	5605.883	185	122.37
Sokoto	0.953	139.653	279.306	726.196	45	47.22
Kebbi	1.388	361.581	723.162	1880.22	187.5	135.1
Zamfara	1.338	349.275	698.550	1816.23	163	121.87
Katsina	1.385	670.054	1340.108	3484.28	165	119.15
Jigawa	1.514	318.467	636.935	1656.03	200	132.08
Kano	2.211	982.05	1964.1	5106.66	206.5	93.41
Kaduna	2.189	2141.213	4282.427	11134.31	181	82.68
Plateau	2.384	1257.915	2515.83	6541.158	198.9	83.45
Nassarawa	1.907	550.043	1100.085	2860.221	125.8	65.98
Abuja	1.888	364.191	728.383	1893.795	105.5	55.88
Niger	1.888	1459.872	2919.745	7591.336	155	82.09
Kwara	1.726	573.383	1146.766	2981.592	217.3	125.89
Kogi	1.539	848.162	1696.324	4410.442	75.5	49.06
Benue	1.878	582.244	1164.487	3027.667	127.8	68.06
Oyo	1.483	635.442	1270.884	3304.299	103.8	70.01
Osun	2.006	421.469	842.937	2191.637	110	54.84
Ekiti	1.644	607.922	1215.844	3161.194	175	106.45
Ondo	2.694	1006.785	2013.57	5235.283	185.9	69.01
Ogun	1.748	927.115	1854.23	4820.998	104.8	59.96
Lagos	2.205	426.926	853.852	2220.016	183.5	83.21
Ebonyi	1.991	171.810	343.621	893.414	166	83.36
Enugu	1.666	322.889	645.777	1679.020	283.3	170.07
Anambra	2.026	203.843	407.685	1059.982	60	29.62
Imo	1.890	361.933	723.865	1882.049	250	132.3

Abia	1.305	216.290	432.580	1124.707	180.8	138.53
Edo	1.633	251.976	503.952	1310.275	240	147.01
Delta	1.887	422.718	845.436	2198.133	72.3	38.32
Bayelsa	1.845	106.887	213.774	555.811	448.6	243.21
Rivers	1.237	215.979	431.959	1123.092	138	111.56
Awka-Ibom	1.178	179.496	358.993	933.381	652.5	554.09
Cross River	2.095	472.659	945.319	2457.828	164.7	78.635

Terms	**Description**	**Measurement Unit**
MResidue	Mean Residue	Thousand Tons
Mharvest	Mean Harvest	Thousand Tons
MRenegpot	Mean Renewable Energy Potential of Crop Residue	Gigajoule
MCostProd	Mean Production Cost Per Unit Land Area	Thousand Naira per hectare
MProdul	Mean Productivity Per Unit Land	Tons per unit hectare
MCCPRI	Mean Combined Cost Productivity Ratio Index	Thousand naira per ton

Source: National Agricultural Extension and Research Liaison Services (2017)

APPENDIX 9: Location-Allocation Optimization Solution Report Showing Optimal Sites

```
Global optimal solution found.
 Objective value:                              4562998
 Objective bound:                              4562998
 Infeasibilities:                              0.000000
 Extended solver steps:                               0
 Total solver iterations:                           119
 Elapsed runtime seconds:                          0.79
 Model Class:                                      MILP
 Total variables:                     49
 Nonlinear variables:                  0
 Integer variables:                    7
 Total constraints:                   50
 Nonlinear constraints:                0
 Total nonzeros:                     175
 Nonlinear nonzeros:                   0

                         Variable           Value        Reduced Cost
                                P        3.000000            0.000000
                             A(A)        111.0000            0.000000
                             A(B)        221.0000            0.000000
                             A(C)        36.00000            0.000000
                             A(D)        139.0000            0.000000
                             A(E)        13.00000            0.000000
                             A(F)        78.00000            0.000000
                             Y(1)        0.000000           -72705.00
                             Y(2)        0.000000           -40737.00
                             Y(3)        1.000000            0.000000
                            Y( 4)        0.000000           -495241.0
                             Y(5)        1.000000            0.000000
                             Y(6)        0.000000           -366081.0
                             Y(7)        1.000000            0.000000
                          D(A, 1)        1743.000            0.000000
                          D(A, 2)        2031.000            0.000000
                          D(A, 3)        2398.000            0.000000
                          D(A, 4)        43912.00            0.000000
                          D(A, 5)        11888.00            0.000000
                          D(A, 6)        56333.00            0.000000
                          D(A, 7)        53280.00            0.000000
                          D(B, 1)        16774.00            0.000000
                          D(B, 2)        16199.00            0.000000
                          D(B, 3)        15868.00            0.000000
                          D(B, 4)        107384.0            0.000000
                          D(B, 5)        36907.00            0.000000
```

D(B, 6)	131849.0	0.000000
D(B, 7)	114566.0	0.000000
D(C, 1)	14893.00	0.000000
D(C, 2)	14987.00	0.000000
D(C, 3)	14908.00	0.000000
D(C, 4)	122.0000	0.000000
D(C, 5)	12470.00	0.000000
D(C, 6)	4198.000	0.000000
D(C, 7)	15916.00	0.000000
D(D, 1)	16889.00	0.000000
D(D, 2)	17111.00	0.000000
D(D, 3)	16388.00	0.000000
D(D, 4)	48928.00	0.000000
D(D, 5)	1793.000	0.000000
D(D, 6)	62911.00	0.000000
D(D, 7)	50540.00	0.000000
D(E, 1)	6941.000	0.000000
D(E, 2)	6973.000	0.000000
D(E, 3)	6969.000	0.000000
D(E, 4)	1808.000	0.000000
D(E, 5)	5905.000	0.000000
D(E, 6)	456.0000	0.000000
D(E, 7)	5709.000	0.000000
D(F, 1)	37783.00	0.000000
D(F, 2)	37892.00	0.000000
D(F, 3)	37440.00	0.000000
D(F, 4)	34546.00	0.000000
D(F, 5)	29117.00	0.000000
D(F, 6)	36005.00	0.000000
D(F, 7)	226.0000	0.000000
X(A, 1)	0.000000	0.000000
X(A, 2)	0.000000	0.000000
X(A, 3)	1.000000	0.000000
X(A, 4)	0.000000	4608054.
X(A, 5)	0.000000	1053390.
X(A, 6)	0.000000	5986785.
X(A, 7)	0.000000	5647902.
X(B, 1)	0.000000	200226.0
X(B, 2)	0.000000	73151.00
X(B, 3)	1.000000	0.000000
X(B, 4)	0.000000	0.2022504E+08
X(B, 5)	0.000000	4649619.
X(B, 6)	0.000000	0.2563180E+08
X(B, 7)	0.000000	0.2181226E+08
X(C, 1)	0.000000	87228.00
X(C, 2)	0.000000	90612.00
X(C, 3)	0.000000	87768.00
X(C, 4)	0.000000	0.000000
X(C, 5)	1.000000	0.000000
X(C, 6)	0.000000	0.000000

X(C, 7)	0.000000	124056.0
X(D, 1)	0.000000	2098344.
X(D, 2)	0.000000	2129202.
X(D, 3)	0.000000	2028705.
X(D, 4)	0.000000	6551765.
X(D, 5)	1.000000	0.000000
X(D, 6)	0.000000	8495402.
X(D, 7)	0.000000	6775833.
X(E, 1)	0.000000	16016.00
X(E, 2)	0.000000	16432.00
X(E, 3)	0.000000	16380.00
X(E, 4)	0.000000	0.000000
X(E, 5)	0.000000	2548.000
X(E, 6)	0.000000	0.000000
X(E, 7)	1.000000	0.000000
X(F, 1)	0.000000	2929446.
X(F, 2)	0.000000	2937948.
X(F, 3)	0.000000	2902692.
X(F, 4)	0.000000	2676960.
X(F, 5)	0.000000	2253498.
X(F, 6)	0.000000	2790762.
X(F, 7)	1.000000	0.000000

Row	**Slack or Surplus**	**Dual Price**
1	4562998.	-1.000000
2	0.000000	-266178.0
3	0.000000	-3506828.
4	0.000000	-448920.0
5	0.000000	-249227.0
6	0.000000	-74217.00
7	0.000000	-17628.00
8	0.000000	72705.00
9	0.000000	40737.00
10	0.000000	0.000000
11	0.000000	0.000000
12	1.000000	0.000000
13	0.000000	0.000000
14	1.000000	0.000000
15	0.000000	0.000000
16	0.000000	0.000000
17	0.000000	0.000000
18	0.000000	0.000000
19	1.000000	0.000000
20	0.000000	0.000000
21	1.000000	0.000000
22	0.000000	0.000000
23	0.000000	0.000000
24	1.000000	0.000000
25	0.000000	444528.0
26	0.000000	0.000000

27	0.000000	297792.0
28	1.000000	0.000000
29	0.000000	0.000000
30	0.000000	0.000000
31	1.000000	0.000000
32	0.000000	0.000000
33	0.000000	0.000000
34	0.000000	0.000000
35	1.000000	0.000000
36	0.000000	0.000000
37	0.000000	0.000000
38	1.000000	0.000000
39	0.000000	50713.00
40	1.000000	0.000000
41	0.000000	68289.00
42	0.000000	0.000000
43	0.000000	0.000000
44	0.000000	0.000000
45	1.000000	0.000000
46	0.000000	0.000000
47	1.000000	0.000000
48	0.000000	0.000000
49	0.000000	0.000000
50	0.000000	0.000000

LINGO Solution Report Showing Optimal Facility Sites when *p* = 3

```
Global optimal solution found.
Objective value:                                 9598543
Objective bound:                                 9598543
Infeasibilities:                                 0.000000
Extended solver steps:                                 0
Total solver iterations:                               0
Elapsed runtime seconds:                            0.13
Model Class:                                        MILP
Total variables:                    49
Nonlinear variables:                 0
Integer variables:                   7
Total constraints:                  50
Nonlinear constraints:               0
Total nonzeros:                    175
Nonlinear nonzeros:                  0

                     Variable           Value        Reduced Cost
                            P        1.000000            0.000000
                         A(A)        111.0000            0.000000
                         A(B)        221.0000            0.000000
```

A(C)	36.00000	0.000000
A(D)	139.0000	0.000000
A(E)	13.00000	0.000000
A(F)	78.00000	0.000000
Y(1)	0.000000	-73609.00
Y(2)	0.000000	-40737.00
Y(3)	**1.000000**	**0.000000**
Y(4)	0.000000	-825121.0
Y(5)	0.000000	-2779499.
Y(6)	0.000000	-582159.0
Y(7)	0.000000	-2919072.
D(A, 1)	1743.000	0.000000
D(A, 2)	2031.000	0.000000
D(A, 3)	2398.000	0.000000
D(A, 4)	43912.00	0.000000
D(A, 5)	11888.00	0.000000
D(A, 6)	56333.00	0.000000
D(A, 7)	53280.00	0.000000
D(B, 1)	16774.00	0.000000
D(B, 2)	16199.00	0.000000
D(B, 3)	15868.00	0.000000
D(B, 4)	107384.0	0.000000
D(B, 5)	36907.00	0.000000
D(B, 6)	131849.0	0.000000
D(B, 7)	114566.0	0.000000
D(C, 1)	14893.00	0.000000
D(C, 2)	14987.00	0.000000
D(C, 3)	14908.00	0.000000
D(C, 4)	122.0000	0.000000
D(C, 5)	12470.00	0.000000
D(C, 6)	4198.000	0.000000
D(C, 7)	15916.00	0.000000
D(D, 1)	16889.00	0.000000
D(D, 2)	17111.00	0.000000
D(D, 3)	16388.00	0.000000
D(D, 4)	48928.00	0.000000
D(D, 5)	1793.000	0.000000
D(D, 6)	62911.00	0.000000
D(D, 7)	50540.00	0.000000
D(E, 1)	6941.000	0.000000
D(E, 2)	6973.000	0.000000
D(E, 3)	6969.000	0.000000
D(E, 4)	1808.000	0.000000
D(E, 5)	5905.000	0.000000
D(E, 6)	456.0000	0.000000
D(E, 7)	5709.000	0.000000
D(F, 1)	37783.00	0.000000
D(F, 2)	37892.00	0.000000
D(F, 3)	37440.00	0.000000
D(F, 4)	34546.00	0.000000

D(F, 5)	29117.00	0.000000
D(F, 6)	36005.00	0.000000
D(F, 7)	226.0000	0.000000
X(A, 1)	0.000000	0.000000
X(A, 2)	0.000000	0.000000
X(A, 3)	1.000000	0.000000
X(A, 4)	0.000000	4608054.
X(A, 5)	0.000000	1053390.
X(A, 6)	0.000000	5986785.
X(A, 7)	0.000000	5647902.
X(B, 1)	0.000000	200226.0
X(B, 2)	0.000000	73151.00
X(B, 3)	1.000000	0.000000
X(B, 4)	0.000000	0.2022504E+08
X(B, 5)	0.000000	4649619.
X(B, 6)	0.000000	0.2563180E+08
X(B, 7)	0.000000	0.2181226E+08
X(C, 1)	0.000000	0.000000
X(C, 2)	0.000000	2844.000
X(C, 3)	1.000000	0.000000
X(C, 4)	0.000000	0.000000
X(C, 5)	0.000000	0.000000
X(C, 6)	0.000000	0.000000
X(C, 7)	0.000000	36288.00
X(D, 1)	0.000000	69639.00
X(D, 2)	0.000000	100497.0
X(D, 3)	1.000000	0.000000
X(D, 4)	0.000000	4523060.
X(D, 5)	0.000000	0.000000
X(D, 6)	0.000000	6466697.
X(D, 7)	0.000000	4747128.
X(E, 1)	0.000000	0.000000
X(E, 2)	0.000000	52.00000
X(E, 3)	1.000000	0.000000
X(E, 4)	0.000000	0.000000
X(E, 5)	0.000000	0.000000
X(E, 6)	0.000000	0.000000
X(E, 7)	0.000000	0.000000
X(F, 1)	0.000000	26754.00
X(F, 2)	0.000000	35256.00
X(F, 3)	1.000000	0.000000
X(F, 4)	0.000000	0.000000
X(F, 5)	0.000000	0.000000
X(F, 6)	0.000000	0.000000
X(F, 7)	0.000000	0.000000

Row	**Slack or Surplus**	**Dual Price**
1	9598543.	-1.000000
2	0.000000	-266178.0
3	0.000000	-3506828.

4	0.000000	-536688.0
5	0.000000	-2277932.
6	0.000000	-90597.00
7	0.000000	-2920320.
8	0.000000	72705.00
9	0.000000	40737.00
10	0.000000	0.000000
11	0.000000	0.000000
12	0.000000	0.000000
13	0.000000	0.000000
14	0.000000	0.000000
15	0.000000	0.000000
16	0.000000	0.000000
17	0.000000	0.000000
18	0.000000	0.000000
19	0.000000	0.000000
20	0.000000	0.000000
21	0.000000	0.000000
22	0.000000	540.0000
23	0.000000	0.000000
24	0.000000	0.000000
25	0.000000	532296.0
26	0.000000	87768.00
27	0.000000	385560.0
28	0.000000	0.000000
29	0.000000	0.000000
30	0.000000	0.000000
31	0.000000	0.000000
32	0.000000	0.000000
33	0.000000	2028705.
34	0.000000	0.000000
35	0.000000	0.000000
36	0.000000	364.0000
37	0.000000	0.000000
38	0.000000	0.000000
39	0.000000	67093.00
40	0.000000	13832.00
41	0.000000	84669.00
42	0.000000	16380.00
43	0.000000	0.000000
44	0.000000	0.000000
45	0.000000	0.000000
46	0.000000	225732.0
47	0.000000	649194.0
48	0.000000	111930.0
49	0.000000	2902692.
50	0.000000	0.000000

LINGO Solution Report Showing Optimal Facility Sites when p = 1

```
Global optimal solution found.
Objective value:                              6679471
Objective bound:                              6679471
Infeasibilities:                              0.000000
Extended solver steps:                               1
Total solver iterations:                           175
Elapsed runtime seconds:                          0.40
Model Class:                                      MILP
Total variables:                   49
Nonlinear variables:                0
Integer variables:                  7
Total constraints:                 50
Nonlinear constraints:              0
Total nonzeros:                   175
Nonlinear nonzeros:                 0
```

Variable	Value	Reduced Cost
P	2.000000	0.000000
A(A)	111.0000	0.000000
A(B)	221.0000	0.000000
A(C)	36.00000	0.000000
A(D)	139.0000	0.000000
A(E)	13.00000	0.000000
A(F)	78.00000	0.000000
Y(1)	0.000000	-73245.00
Y(2)	0.000000	-40737.00
Y(3)	**1.000000**	**0.000000**
Y(4)	0.000000	-583009.0
Y(5)	0.000000	-2116473.
Y(6)	0.000000	-453849.0
Y(7)	**1.000000**	**0.000000**
D(A, 1)	1743.000	0.000000
D(A, 2)	2031.000	0.000000
D(A, 3)	2398.000	0.000000
D(A, 4)	43912.00	0.000000
D(A, 5)	11888.00	0.000000
D(A, 6)	56333.00	0.000000
D(A, 7)	53280.00	0.000000
D(B, 1)	16774.00	0.000000
D(B, 2)	16199.00	0.000000
D(B, 3)	15868.00	0.000000
D(B, 4)	107384.0	0.000000
D(B, 5)	36907.00	0.000000
D(B, 6)	131849.0	0.000000
D(B, 7)	114566.0	0.000000
D(C, 1)	14893.00	0.000000
D(C, 2)	14987.00	0.000000

D(C, 3)	14908.00	0.000000
D(C, 4)	122.0000	0.000000
D(C, 5)	12470.00	0.000000
D(C, 6)	4198.000	0.000000
D(C, 7)	15916.00	0.000000
D(D, 1)	16889.00	0.000000
D(D, 2)	17111.00	0.000000
D(D, 3)	16388.00	0.000000
D(D, 4)	48928.00	0.000000
D(D, 5)	1793.000	0.000000
D(D, 6)	62911.00	0.000000
D(D, 7)	50540.00	0.000000
D(E, 1)	6941.000	0.000000
D(E, 2)	6973.000	0.000000
D(E, 3)	6969.000	0.000000
D(E, 4)	1808.000	0.000000
D(E, 5)	5905.000	0.000000
D(E, 6)	456.0000	0.000000
D(E, 7)	5709.000	0.000000
D(F, 1)	37783.00	0.000000
D(F, 2)	37892.00	0.000000
D(F, 3)	37440.00	0.000000
D(F, 4)	34546.00	0.000000
D(F, 5)	29117.00	0.000000
D(F, 6)	36005.00	0.000000
D(F, 7)	226.0000	0.000000
X(A, 1)	0.000000	0.000000
X(A, 2)	0.000000	0.000000
X(A, 3)	1.000000	0.000000
X(A, 4)	0.000000	4608054.
X(A, 5)	0.000000	1053390.
X(A, 6)	0.000000	5986785.
X(A, 7)	0.000000	5647902.
X(B, 1)	0.000000	200226.0
X(B, 2)	0.000000	73151.00
X(B, 3)	1.000000	0.000000
X(B, 4)	0.000000	0.2022504E+08
X(B, 5)	0.000000	4649619.
X(B, 6)	0.000000	0.2563180E+08
X(B, 7)	0.000000	0.2181226E+08
X(C, 1)	0.000000	0.000000
X(C, 2)	0.000000	2844.000
X(C, 3)	1.000000	0.000000
X(C, 4)	0.000000	0.000000
X(C, 5)	0.000000	0.000000
X(C, 6)	0.000000	0.000000
X(C, 7)	0.000000	36288.00
X(D, 1)	0.000000	69639.00
X(D, 2)	0.000000	100497.0
X(D, 3)	1.000000	0.000000

X(D, 4)	0.000000	4523060.
X(D, 5)	0.000000	0.000000
X(D, 6)	0.000000	6466697.
X(D, 7)	0.000000	4747128.
X(E, 1)	0.000000	16016.00
X(E, 2)	0.000000	16432.00
X(E, 3)	0.000000	16380.00
X(E, 4)	0.000000	0.000000
X(E, 5)	0.000000	2548.000
X(E, 6)	0.000000	0.000000
X(E, 7)	1.000000	0.000000
X(F, 1)	0.000000	2929446.
X(F, 2)	0.000000	2937948.
X(F, 3)	0.000000	2902692.
X(F, 4)	0.000000	2676960.
X(F, 5)	0.000000	2253498.
X(F, 6)	0.000000	2790762.
X(F, 7)	1.000000	0.000000

Row	**Slack or Surplus**	**Dual Price**
1	6679471.	-1.000000
2	0.000000	-266178.0
3	0.000000	-3506828.
4	0.000000	-536688.0
5	0.000000	-2277932.
6	0.000000	-74217.00
7	0.000000	-17628.00
8	0.000000	72705.00
9	0.000000	40737.00
10	0.000000	0.000000
11	0.000000	0.000000
12	0.000000	0.000000
13	0.000000	0.000000
14	1.000000	0.000000
15	0.000000	0.000000
16	0.000000	0.000000
17	0.000000	0.000000
18	0.000000	0.000000
19	0.000000	0.000000
20	0.000000	0.000000
21	1.000000	0.000000
22	0.000000	540.0000
23	0.000000	0.000000
24	0.000000	0.000000
25	0.000000	532296.0
26	0.000000	87768.00
27	0.000000	385560.0
28	1.000000	0.000000
29	0.000000	0.000000
30	0.000000	0.000000

31	0.000000	0.000000
32	0.000000	0.000000
33	0.000000	2028705.
34	0.000000	0.000000
35	1.000000	0.000000
36	0.000000	0.000000
37	0.000000	0.000000
38	1.000000	0.000000
39	0.000000	50713.00
40	0.000000	0.000000
41	0.000000	68289.00
42	0.000000	0.000000
43	0.000000	0.000000
44	0.000000	0.000000
45	1.000000	0.000000
46	0.000000	0.000000
47	0.000000	0.000000
48	0.000000	0.000000
49	0.000000	0.000000
50	0.000000	0.000000

LINGO Solution Report Showing Optimal Facility Sites when *p* = 2

```
  Global optimal solution found.
Objective value:                              4067757
Objective bound:                              4067757
Infeasibilities:                              0.000000
Extended solver steps:                               2
Total solver iterations:                            93
Elapsed runtime seconds:                          0.23
Model Class:                                      MILP
Total variables:                    49
Nonlinear variables:                 0
Integer variables:                   7
Total constraints:                  50
Nonlinear constraints:               0
Total nonzeros:                    175
Nonlinear nonzeros:                  0
```

Variable	Value	Reduced Cost
P	4.000000	0.000000
A(A)	111.0000	0.000000
A(B)	221.0000	0.000000
A(C)	36.00000	0.000000
A(D)	139.0000	0.000000
A(E)	13.00000	0.000000
A(F)	78.00000	0.000000

Y(1)	0.000000	-72705.00
Y(2)	0.000000	-40737.00
Y(3)	**1.000000**	**0.000000**
Y(4)	**1.000000**	**0.000000**
Y(5)	**1.000000**	**0.000000**
Y(6)	0.000000	-17576.00
Y(7)	**1.000000**	**0.000000**
D(A, 1)	1743.000	0.000000
D(A, 2)	2031.000	0.000000
D(A, 3)	2398.000	0.000000
D(A, 4)	43912.00	0.000000
D(A, 5)	11888.00	0.000000
D(A, 6)	56333.00	0.000000
D(A, 7)	53280.00	0.000000
D(B, 1)	16774.00	0.000000
D(B, 2)	16199.00	0.000000
D(B, 3)	15868.00	0.000000
D(B, 4)	107384.0	0.000000
D(B, 5)	36907.00	0.000000
D(B, 6)	131849.0	0.000000
D(B, 7)	114566.0	0.000000
D(C, 1)	14893.00	0.000000
D(C, 2)	14987.00	0.000000
D(C, 3)	14908.00	0.000000
D(C, 4)	122.0000	0.000000
D(C, 5)	12470.00	0.000000
D(C, 6)	4198.000	0.000000
D(C, 7)	15916.00	0.000000
D(D, 1)	16889.00	0.000000
D(D, 2)	17111.00	0.000000
D(D, 3)	16388.00	0.000000
D(D, 4)	48928.00	0.000000
D(D, 5)	1793.000	0.000000
D(D, 6)	62911.00	0.000000
D(D, 7)	50540.00	0.000000
D(E, 1)	6941.000	0.000000
D(E, 2)	6973.000	0.000000
D(E, 3)	6969.000	0.000000
D(E, 4)	1808.000	0.000000
D(E, 5)	5905.000	0.000000
D(E, 6)	456.0000	0.000000
D(E, 7)	5709.000	0.000000
D(F, 1)	37783.00	0.000000
D(F, 2)	37892.00	0.000000
D(F, 3)	37440.00	0.000000
D(F, 4)	34546.00	0.000000
D(F, 5)	29117.00	0.000000
D(F, 6)	36005.00	0.000000
D(F, 7)	226.0000	0.000000
X(A, 1)	0.000000	0.000000

X(A, 2)	0.000000	0.000000
X(A, 3)	1.000000	0.000000
X(A, 4)	0.000000	4608054.
X(A, 5)	0.000000	1053390.
X(A, 6)	0.000000	5986785.
X(A, 7)	0.000000	5647902.
X(B, 1)	0.000000	200226.0
X(B, 2)	0.000000	73151.00
X(B, 3)	1.000000	0.000000
X(B, 4)	0.000000	0.2022504E+08
X(B, 5)	0.000000	4649619.
X(B, 6)	0.000000	0.2563180E+08
X(B, 7)	0.000000	0.2181226E+08
X(C, 1)	0.000000	531756.0
X(C, 2)	0.000000	535140.0
X(C, 3)	0.000000	532296.0
X(C, 4)	1.000000	0.000000
X(C, 5)	0.000000	444528.0
X(C, 6)	0.000000	146736.0
X(C, 7)	0.000000	568584.0
X(D, 1)	0.000000	2098344.
X(D, 2)	0.000000	2129202.
X(D, 3)	0.000000	2028705.
X(D, 4)	0.000000	6551765.
X(D, 5)	1.000000	0.000000
X(D, 6)	0.000000	8495402.
X(D, 7)	0.000000	6775833.
X(E, 1)	0.000000	66729.00
X(E, 2)	0.000000	67145.00
X(E, 3)	0.000000	67093.00
X(E, 4)	1.000000	0.000000
X(E, 5)	0.000000	53261.00
X(E, 6)	0.000000	0.000000
X(E, 7)	0.000000	50713.00
X(F, 1)	0.000000	2929446.
X(F, 2)	0.000000	2937948.
X(F, 3)	0.000000	2902692.
X(F, 4)	0.000000	2676960.
X(F, 5)	0.000000	2253498.
X(F, 6)	0.000000	2790762.
X(F, 7)	1.000000	0.000000

Row	**Slack or Surplus**	**Dual Price**
1	4067757.	-1.000000
2	0.000000	-266178.0
3	0.000000	-3506828.
4	0.000000	-4392.000
5	0.000000	-249227.0
6	0.000000	-23504.00
7	0.000000	-17628.00

8	0.000000	72705.00
9	0.000000	40737.00
10	0.000000	0.000000
11	1.000000	0.000000
12	1.000000	0.000000
13	0.000000	0.000000
14	1.000000	0.000000
15	0.000000	0.000000
16	0.000000	0.000000
17	0.000000	0.000000
18	1.000000	0.000000
19	1.000000	0.000000
20	0.000000	0.000000
21	1.000000	0.000000
22	0.000000	0.000000
23	0.000000	0.000000
24	1.000000	0.000000
25	0.000000	0.000000
26	1.000000	0.000000
27	0.000000	0.000000
28	1.000000	0.000000
29	0.000000	0.000000
30	0.000000	0.000000
31	1.000000	0.000000
32	1.000000	0.000000
33	0.000000	0.000000
34	0.000000	0.000000
35	1.000000	0.000000
36	0.000000	0.000000
37	0.000000	0.000000
38	1.000000	0.000000
39	0.000000	0.000000
40	1.000000	0.000000
41	0.000000	17576.00
42	1.000000	0.000000
43	0.000000	0.000000
44	0.000000	0.000000
45	1.000000	0.000000
46	1.000000	0.000000
47	1.000000	0.000000
48	0.000000	0.000000
49	0.000000	0.000000
50	0.000000	0.000000

LINGO Solution Report Showing Optimal Facility Sites when $p = 4$

```
Global optimal solution found.
Objective value:                              3995052
Objective bound:                              3995052
Infeasibilities:                              0.000000
Extended solver steps:                               0
Total solver iterations:                            42
Elapsed runtime seconds:                          0.13
Model Class:                                      MILP
Total variables:                    49
Nonlinear variables:                 0
Integer variables:                   7
Total constraints:                  50
Nonlinear constraints:               0
Total nonzeros:                    175
Nonlinear nonzeros:                  0
```

Variable	Value	Reduced Cost
P	5.000000	0.000000
A(A)	111.0000	0.000000
A(B)	221.0000	0.000000
A(C)	36.00000	0.000000
A(D)	139.0000	0.000000
A(E)	13.00000	0.000000
A(F)	78.00000	0.000000
Y(1)	**1.000000**	**0.000000**
Y(2)	0.000000	0.000000
Y(3)	**1.000000**	**0.000000**
Y(4)	**1.000000**	**0.000000**
Y(5)	**1.000000**	**0.000000**
Y(6)	0.000000	-17576.00
Y(7)	**1.000000**	**0.000000**
D(A, 1)	1743.000	0.000000
D(A, 2)	2031.000	0.000000
D(A, 3)	2398.000	0.000000
D(A, 4)	43912.00	0.000000
D(A, 5)	11888.00	0.000000
D(A, 6)	56333.00	0.000000
D(A, 7)	53280.00	0.000000
D(B, 1)	16774.00	0.000000
D(B, 2)	16199.00	0.000000
D(B, 3)	15868.00	0.000000
D(B, 4)	107384.0	0.000000
D(B, 5)	36907.00	0.000000
D(B, 6)	131849.0	0.000000
D(B, 7)	114566.0	0.000000
D(C, 1)	14893.00	0.000000
D(C, 2)	14987.00	0.000000
D(C, 3)	14908.00	0.000000
D(C, 4)	122.0000	0.000000
D(C, 5)	12470.00	0.000000

D(C, 6)	4198.000	0.000000
D(C, 7)	15916.00	0.000000
D(D, 1)	16889.00	0.000000
D(D, 2)	17111.00	0.000000
D(D, 3)	16388.00	0.000000
D(D, 4)	48928.00	0.000000
D(D, 5)	1793.000	0.000000
D(D, 6)	62911.00	0.000000
D(D, 7)	50540.00	0.000000
D(E, 1)	6941.000	0.000000
D(E, 2)	6973.000	0.000000
D(E, 3)	6969.000	0.000000
D(E, 4)	1808.000	0.000000
D(E, 5)	5905.000	0.000000
D(E, 6)	456.0000	0.000000
D(E, 7)	5709.000	0.000000
D(F, 1)	37783.00	0.000000
D(F, 2)	37892.00	0.000000
D(F, 3)	37440.00	0.000000
D(F, 4)	34546.00	0.000000
D(F, 5)	29117.00	0.000000
D(F, 6)	36005.00	0.000000
D(F, 7)	226.0000	0.000000
X(A, 1)	1.000000	0.000000
X(A, 2)	0.000000	31968.00
X(A, 3)	0.000000	72705.00
X(A, 4)	0.000000	4680759.
X(A, 5)	0.000000	1126095.
X(A, 6)	0.000000	6059490.
X(A, 7)	0.000000	5720607.
X(B, 1)	0.000000	200226.0
X(B, 2)	0.000000	73151.00
X(B, 3)	1.000000	0.000000
X(B, 4)	0.000000	0.2022504E+08
X(B, 5)	0.000000	4649619.
X(B, 6)	0.000000	0.2563180E+08
X(B, 7)	0.000000	0.2181226E+08
X(C, 1)	0.000000	531756.0
X(C, 2)	0.000000	535140.0
X(C, 3)	0.000000	532296.0
X(C, 4)	1.000000	0.000000
X(C, 5)	0.000000	444528.0
X(C, 6)	0.000000	146736.0
X(C, 7)	0.000000	568584.0
X(D, 1)	0.000000	2098344.
X(D, 2)	0.000000	2129202.
X(D, 3)	0.000000	2028705.
X(D, 4)	0.000000	6551765.
X(D, 5)	1.000000	0.000000
X(D, 6)	0.000000	8495402.

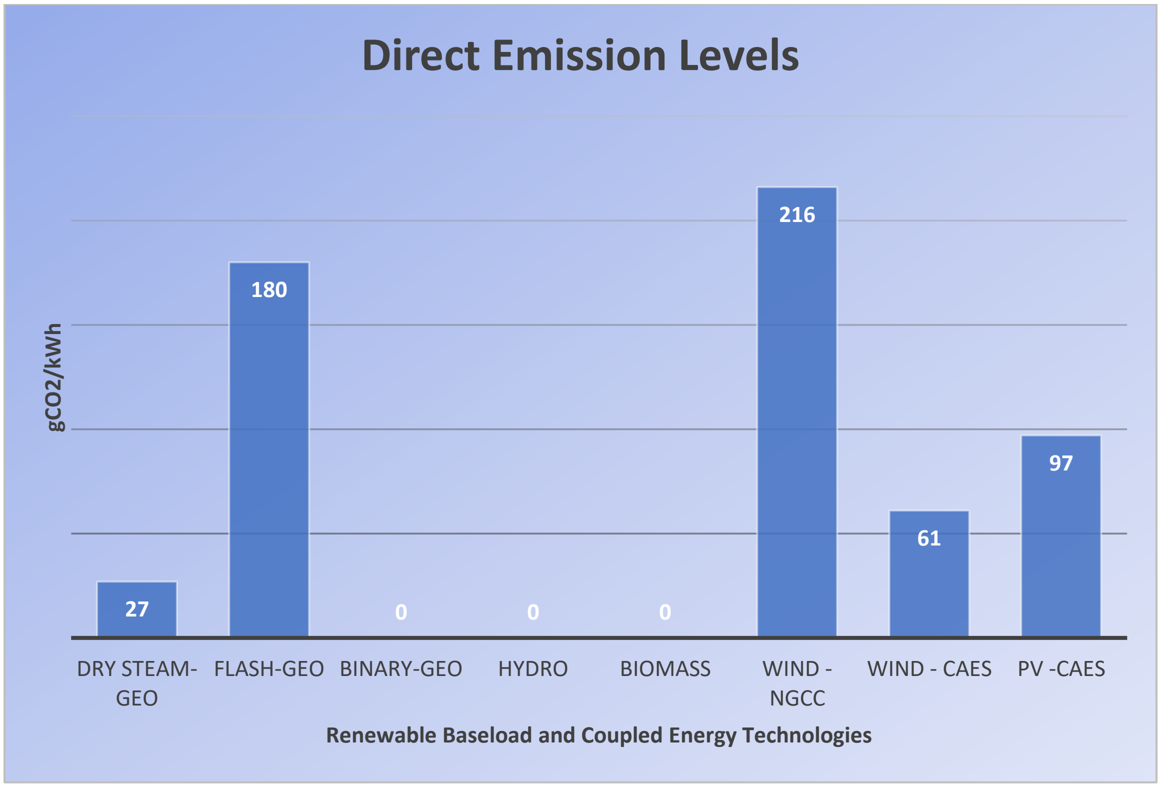
X(D, 7)	0.000000	6775833.
X(E, 1)	0.000000	66729.00
X(E, 2)	0.000000	67145.00
X(E, 3)	0.000000	67093.00
X(E, 4)	1.000000	0.000000
X(E, 5)	0.000000	53261.00
X(E, 6)	0.000000	0.000000
X(E, 7)	0.000000	50713.00
X(F, 1)	0.000000	2929446.
X(F, 2)	0.000000	2937948.
X(F, 3)	0.000000	2902692.
X(F, 4)	0.000000	2676960.
X(F, 5)	0.000000	2253498.
X(F, 6)	0.000000	2790762.
X(F, 7)	1.000000	0.000000

Row	**Slack or Surplus**	**Dual Price**
1	3995052.	-1.000000
2	0.000000	-193473.0
3	0.000000	-3506828.
4	0.000000	-4392.000
5	0.000000	-249227.0
6	0.000000	-23504.00
7	0.000000	-17628.00
8	0.000000	0.000000
9	0.000000	0.000000
10	1.000000	0.000000
11	1.000000	0.000000
12	1.000000	0.000000
13	0.000000	0.000000
14	1.000000	0.000000
15	1.000000	0.000000
16	0.000000	0.000000
17	0.000000	0.000000
18	1.000000	0.000000
19	1.000000	0.000000
20	0.000000	0.000000
21	1.000000	0.000000
22	1.000000	0.000000
23	0.000000	0.000000
24	1.000000	0.000000
25	0.000000	0.000000
26	1.000000	0.000000
27	0.000000	0.000000
28	1.000000	0.000000
29	1.000000	0.000000
30	0.000000	0.000000
31	1.000000	0.000000
32	1.000000	0.000000
33	0.000000	0.000000

34	0.000000	0.000000
35	1.000000	0.000000
36	1.000000	0.000000
37	0.000000	0.000000
38	1.000000	0.000000
39	0.000000	0.000000
40	1.000000	0.000000
41	0.000000	17576.00
42	1.000000	0.000000
43	1.000000	0.000000
44	0.000000	0.000000
45	1.000000	0.000000
46	1.000000	0.000000
47	1.000000	0.000000
48	0.000000	0.000000
49	0.000000	0.000000
50	0.000000	0.000000

LINGO Solution Report Showing Optimal Facility Sites when $p = 5$

APPENDIX 10:_Estimated Direct Emission from Renewable Baseload Technologies vs. Wind/PV Coupled with Storage or Natural Gas

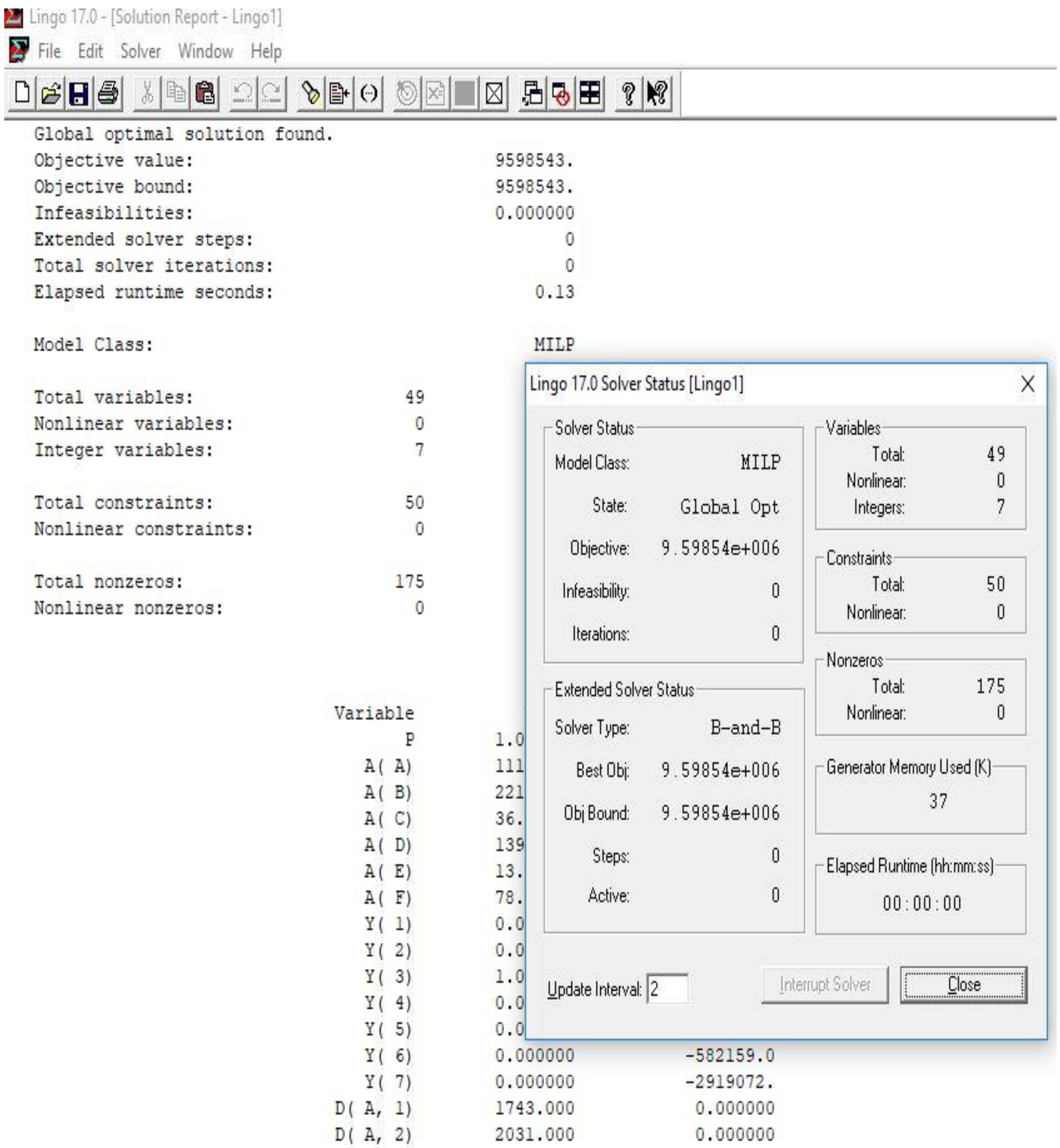


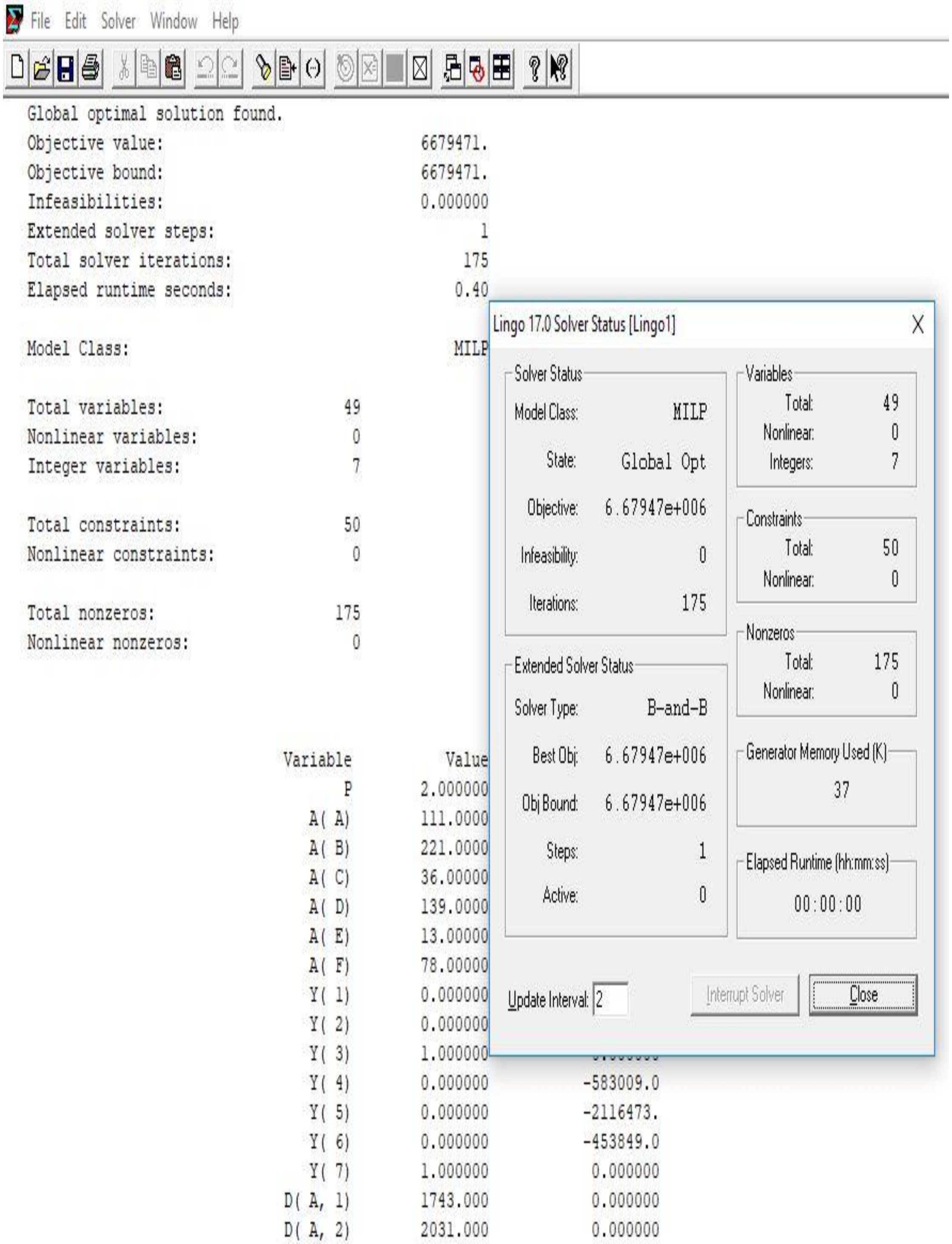
Estimated Direct Emission from Renewable Baseload Technologies vs. Wind/PV Coupled with Storage or Natural Gas **Source**: Matek and Gawell (2015)

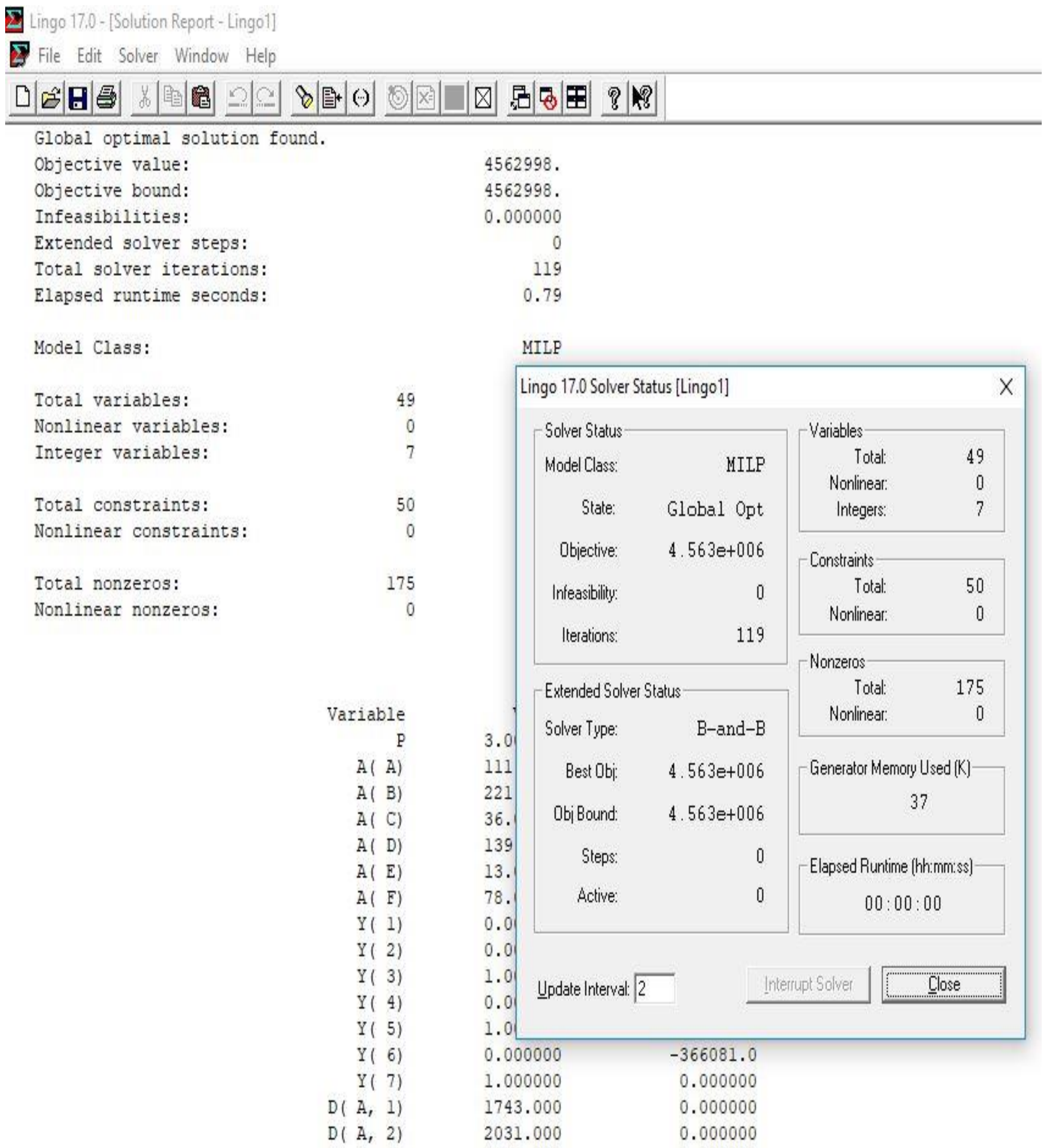
APPENDIX 11: *p*-median problem structured in LINGO

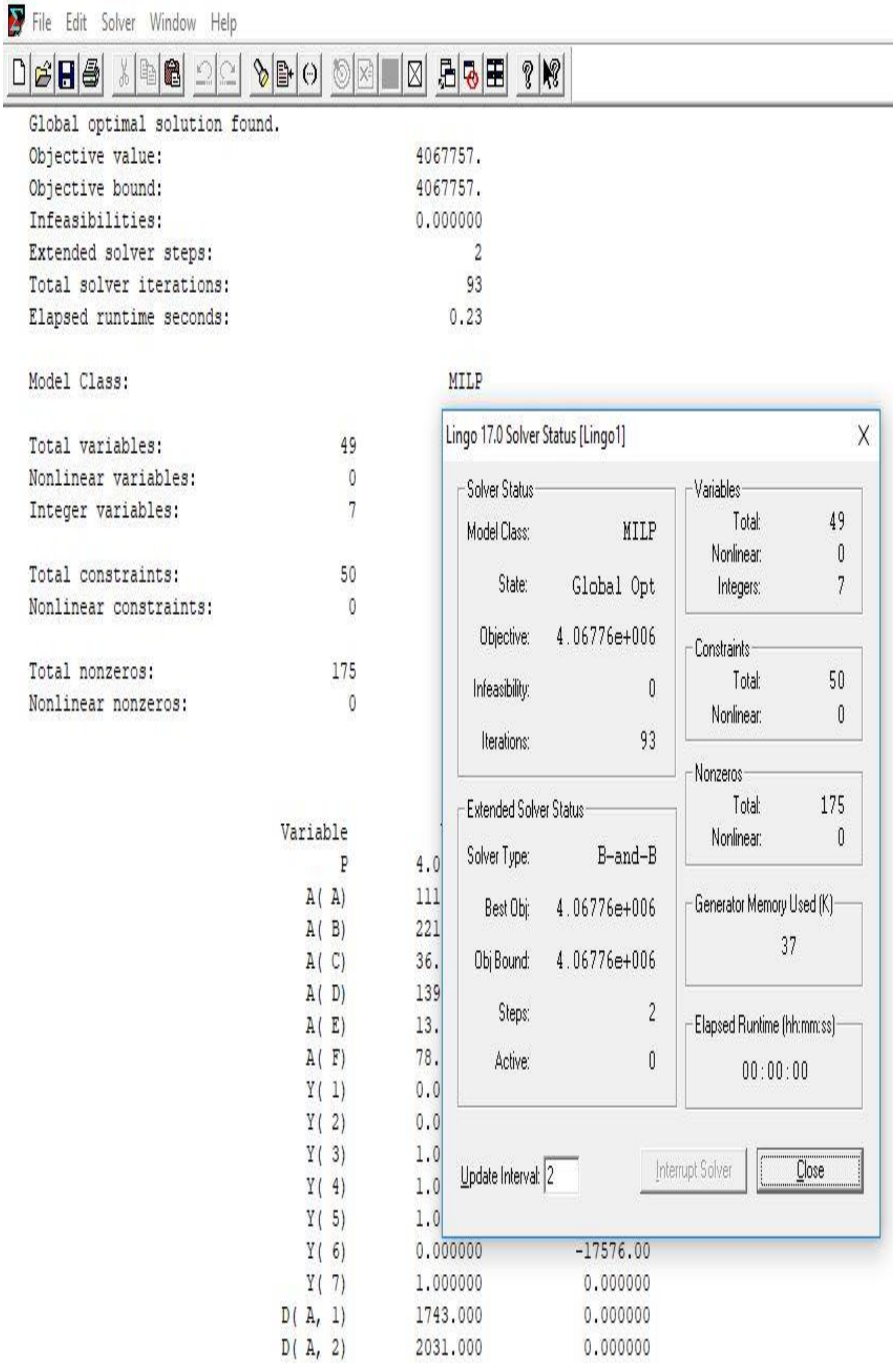
```
! p-Median Problem;
MODEL:
SETS:
  Demand /A,B,C,D,E,F/  : a;
  Sites /1 ..7/ : Y ;
  Allocation (Demand,Sites) : d, X ;
 ENDSETS
! The objective, minimize cost of transmission lines infrastructure measured as
weighted distance; MIN = @SUM (Allocation (i,j): a(i) * d(i,j) * X(i,j));
! Each demand must allocate once to an open facility;
 @FOR( Demand(i):
   @SUM( Sites(j): X( i,j)) = 1; );
! Assignment is restricted to those sites selected for facilities;
@FOR( Demand(i):
 @FOR( Sites(j): X(i,j) < Y(j) ); );
! Open exactly p facilities; @SUM( Sites(j):  Y(j) ) = p ;
! Integer restrictions on the variables;
 @FOR( Sites(j): @BIN(Y(j));  );
! Input data and parameters; DATA:
p = 3;
a = 111, 221, 36, 139, 13, 78;
d = 1743, 2031, 2398, 43912, 11888, 56333, 53280,
     16774, 16199, 15868, 107384, 36907, 131849, 114566,
     14893, 14987, 14908, 122, 12470, 4198, 15916,
     16889, 17111, 16388, 48928, 1793, 62911, 50540,
     6941, 6973, 6969, 1808, 5905, 456, 5709,
     37783, 37892, 37440, 34546, 29117, 36005, 226;
ENDDATA
END
```

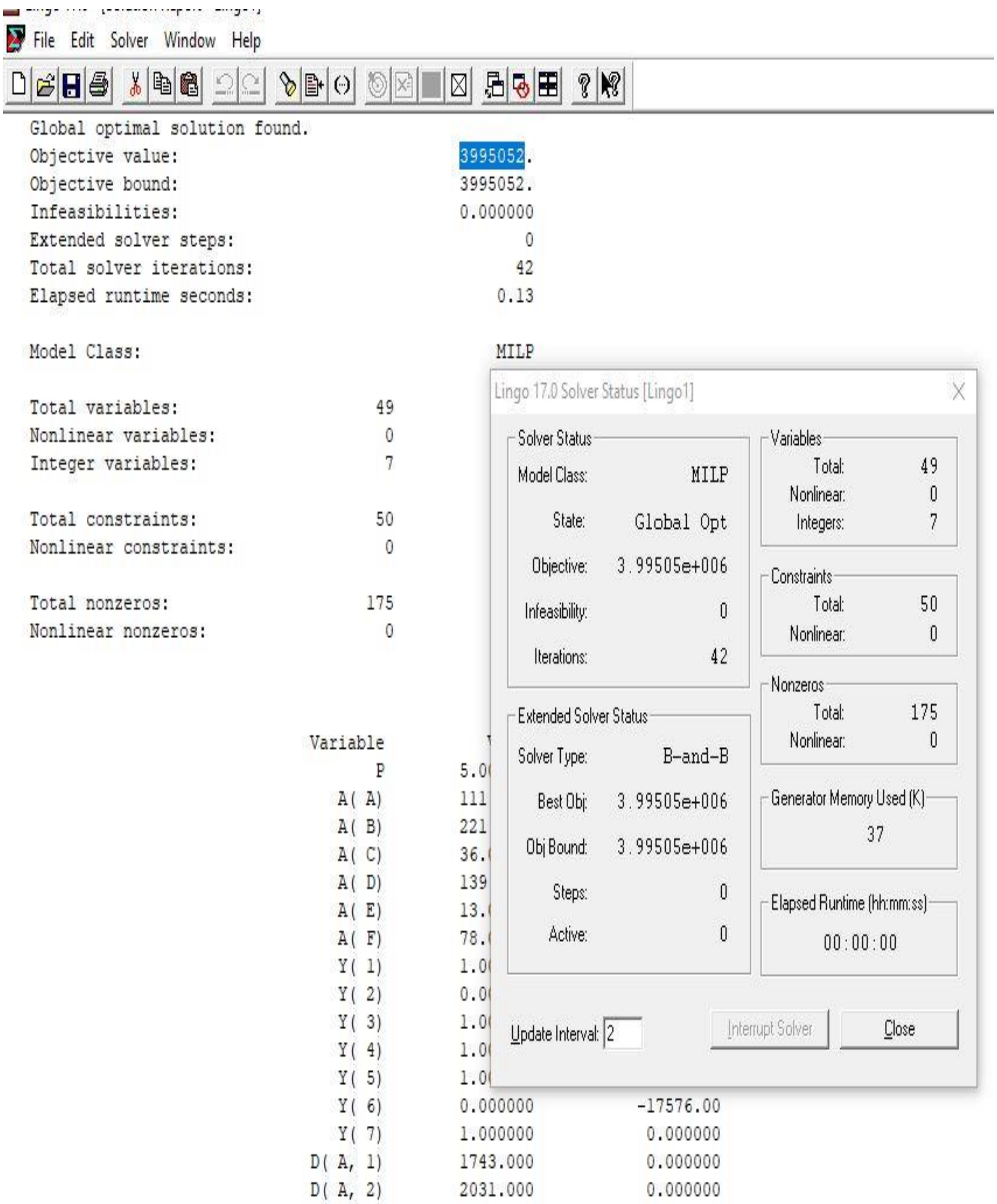
APPENDIX 12: Solution Report Showing Summary of Optimization when p = 1, 2, 3, 4, and 5




File Edit Solver Window Help
Global optimal solution found.
Objective value: 6679471.
Objective bound: 6679471.
Infeasibilities: 0.000000
Extended solver steps: 1
Total solver iterations: 175
Elapsed runtime seconds: 0.40
Model Class: MILP
Total variables: 49
Nonlinear variables: 0
Integer variables: 7
Total constraints: 50
Nonlinear constraints: 0
Total nonzeros: 175
Nonlinear nonzeros: 0
Variable Value
P 2.000000
A(A) 111.0000
A(B) 221.0000
A(C) 36.00000
A(D) 139.0000
A(E) 13.00000
A(F) 78.00000
Y(1) 0.000000
Y(2) 0.000000
Y(3) 1.000000
Y(4) 0.000000 -583009.0
Y(5) 0.000000 -2116473.
Y(6) 0.000000 -453849.0
Y(7) 1.000000 0.000000
D(A, 1) 1743.000 0.000000
D(A, 2) 2031.000 0.000000
Lingo 17.0 Solver Status [Lingo1]
Solver Status
Model Class: MILP
State: Global Opt
Objective: 6.67947e+006
Infeasibility: 0
Iterations: 175
Variables
Total: 49
Nonlinear: 0
Integers: 7
Constraints
Total: 50
Nonlinear: 0
Nonzeros
Total: 175
Nonlinear: 0
Extended Solver Status
Solver Type: B-and-B
Best Obj: 6.67947e+006
Obj Bound: 6.67947e+006
Steps: 1
Active: 0
Generator Memory Used (K)
37
Elapsed Runtime (hh:mm:ss)
00:00:00
Update Interval: 2
Interrupt Solver
Close


Lingo 17.0 - [Solution Report - Lingo1]
File Edit Solver Window Help
Global optimal solution found.
Objective value: 4562998.
Objective bound: 4562998.
Infeasibilities: 0.000000
Extended solver steps: 0
Total solver iterations: 119
Elapsed runtime seconds: 0.79
Model Class: MILP
Total variables: 49
Nonlinear variables: 0
Integer variables: 7
Total constraints: 50
Nonlinear constraints: 0
Total nonzeros: 175
Nonlinear nonzeros: 0
Variable
P 3.0
A(A) 111
A(B) 221
A(C) 36.
A(D) 139
A(E) 13.
A(F) 78.
Y(1) 0.0
Y(2) 0.0
Y(3) 1.0
Y(4) 0.0
Y(5) 1.0
Y(6) 0.000000 -366081.0
Y(7) 1.000000 0.000000
D(A, 1) 1743.000 0.000000
D(A, 2) 2031.000 0.000000
Lingo 17.0 Solver Status [Lingo1]
Solver Status
Model Class: MILP
State: Global Opt
Objective: 4.563e+006
Infeasibility: 0
Iterations: 119
Variables
Total: 49
Nonlinear: 0
Integers: 7
Constraints
Total: 50
Nonlinear: 0
Nonzeros
Total: 175
Nonlinear: 0
Extended Solver Status
Solver Type: B-and-B
Best Obj: 4.563e+006
Obj Bound: 4.563e+006
Steps: 0
Active: 0
Generator Memory Used (K)
37
Elapsed Runtime (hh:mm:ss)
00:00:00
Update Interval: 2
Interrupt Solver
Close


File Edit Solver Window Help
Global optimal solution found.
Objective value: 4067757.
Objective bound: 4067757.
Infeasibilities: 0.000000
Extended solver steps: 2
Total solver iterations: 93
Elapsed runtime seconds: 0.23
Model Class: MILP
Total variables: 49
Nonlinear variables: 0
Integer variables: 7
Total constraints: 50
Nonlinear constraints: 0
Total nonzeros: 175
Nonlinear nonzeros: 0
Variable
P 4.0
A(A) 111
A(B) 221
A(C) 36.
A(D) 139
A(E) 13.
A(F) 78.
Y(1) 0.0
Y(2) 0.0
Y(3) 1.0
Y(4) 1.0
Y(5) 1.0
Y(6) 0.000000 -17576.00
Y(7) 1.000000 0.000000
D(A, 1) 1743.000 0.000000
D(A, 2) 2031.000 0.000000
Lingo 17.0 Solver Status [Lingo1]
Solver Status
Model Class: MILP
State: Global Opt
Objective: 4.06776e+006
Infeasibility: 0
Iterations: 93
Variables
Total: 49
Nonlinear: 0
Integers: 7
Constraints
Total: 50
Nonlinear: 0
Nonzeros
Total: 175
Nonlinear: 0
Extended Solver Status
Solver Type: B-and-B
Best Obj: 4.06776e+006
Obj Bound: 4.06776e+006
Steps: 2
Active: 0
Generator Memory Used (K)
37
Elapsed Runtime (hh:mm:ss)
00:00:00
Update Interval: 2
Interrupt Solver
Close


File Edit Solver Window Help
Global optimal solution found.
Objective value: 3995052.
Objective bound: 3995052.
Infeasibilities: 0.000000
Extended solver steps: 0
Total solver iterations: 42
Elapsed runtime seconds: 0.13
Model Class: MILP
Total variables: 49
Nonlinear variables: 0
Integer variables: 7
Total constraints: 50
Nonlinear constraints: 0
Total nonzeros: 175
Nonlinear nonzeros: 0
Variable
P 5.0
A(A) 111
A(B) 221
A(C) 36.
A(D) 139
A(E) 13.
A(F) 78.
Y(1) 1.0
Y(2) 0.0
Y(3) 1.0
Y(4) 1.0
Y(5) 1.0
Y(6) 0.000000 -17576.00
Y(7) 1.000000 0.000000
D(A, 1) 1743.000 0.000000
D(A, 2) 2031.000 0.000000
Lingo 17.0 Solver Status [Lingo1]
Solver Status
Model Class: MILP
State: Global Opt
Objective: 3.99505e+006
Infeasibility: 0
Iterations: 42
Variables
Total: 49
Nonlinear: 0
Integers: 7
Constraints
Total: 50
Nonlinear: 0
Nonzeros
Total: 175
Nonlinear: 0
Extended Solver Status
Solver Type: B-and-B
Best Obj: 3.99505e+006
Obj Bound: 3.99505e+006
Steps: 0
Active: 0
Generator Memory Used (K)
37
Elapsed Runtime (hh:mm:ss)
00:00:00
Update Interval: 2
Interrupt Solver
Close